Project 2

BWRX-300 SMR vs AP1000 Reactor to Power Data Centers

(Electricity + Heat Reuse)

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Dr. Richard Simmons

Written by: Parth Patel

Georgia Tech College of Engineering

George W. Woodruff School of Mechanical Engineering

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Abstract

This project evaluates the technical and economic feasibility of integrating nuclear power directly with a hyperscale liquid-cooled data center to address the escalating energy demands of artificial intelligence (AI) infrastructure. Two reactor technologies were modeled and compared: the Westinghouse AP1000, a gigawatt-scale Pressurized Water Reactor (PWR), and the GE-Hitachi BWRX-300, a Small Modular Reactor (SMR) utilizing a direct-cycle boiling water design. Thermodynamic models were developed in Engineering Equation Solver (EES) to simulate Rankine cycles, secondary cooling loops, and tertiary heat rejection systems for both plants. The analysis reveals that while the AP1000 offers superior economies of scale with a Levelized Cost of Electricity (LCOE) of $0.196/kWh, its 1,224 MW output is excessively oversized for a single 100 MW data center, necessitating significant grid export infrastructure. Conversely, the BWRX-300, with an output of 294 MW and an LCOE of $0.268/kWh, provides a modular capacity that more closely aligns with single-site facility demands while reducing initial capital exposure and water consumption by 84%. Parametric studies on environmental sensitivity, turbine degradation, and cycle optimization highlight that both designs face efficiency penalties of up to 9% during peak summer conditions, underscoring the importance of robust cooling system design. Ultimately, the study finds that while the AP1000 is more cost efficient for large scale data center projects, the BWRX-300 SMR offers an easier barrier to entry for smaller scale projects.

Introduction

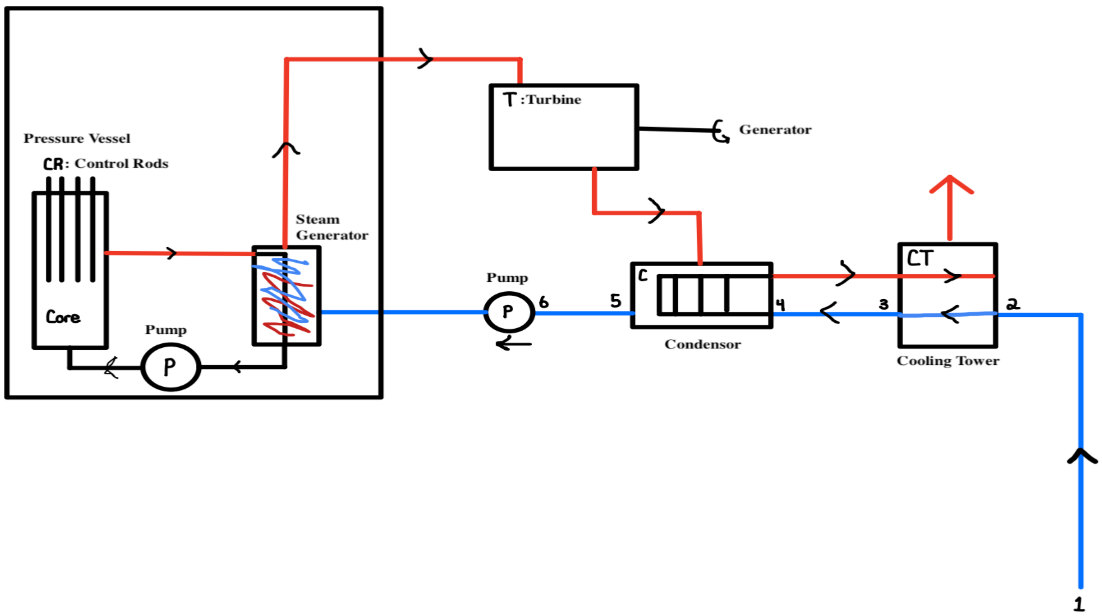
The rapid expansion of artificial intelligence (AI) and Large Language Model (LLM) training has created an unprecedented surge in data center energy consumption. Modern hyperscale facilities are transitioning from traditional air cooling to high-density liquid-to-chip cooling to manage rack power densities exceeding 100 kW. However, the electrical grid faces growing congestion and reliability challenges, threatening the 24/7 uptime required by these facilities. Integrating nuclear power directly with data centers offers a transformative solution: a carbon-free, baseload power source that eliminates transmission reliance and provides high-grade thermal reliability. This project investigates the thermal and economic viability of two distinct nuclear technologies for this application. The first is the Westinghouse AP1000, a proven two-loop PWR producing over 1,100 MWe, representing the traditional large-scale approach. The second is the GE-Hitachi BWRX-300, a 300 MWe Small Modular Reactor (SMR) that uses a simplified direct cycle BWR architecture designed for modular deployment. The study employs comprehensive thermodynamic modeling to simulate reactor cores, steam cycles, and cooling networks. A detailed fluid-flow analysis sizes the critical interface between the nuclear plant and the data center: a network of YORK YVAA 500 chillers and liquid coolant loops required to reject 42 MW of chip heat. By quantifying the thermodynamic efficiency, exergy destruction, water consumption, and economic costs (LCOE) of both systems, this report determines whether the scale of a traditional PWR provides a cost advantage that outweighs the flexibility and lower capital risk of the SMR.

Design: Westinghouse AP1000 Reactor

System Description

The Westinghouse AP1000 is modeled as a two-loop Pressurized Water Reactor (PWR) designed to separate the radioactive primary coolant from the power-generating steam cycle. The system architecture is divided into three distinct fluid loops: the primary loop containing the reactor core, the secondary loop operating as a Rankine cycle, and the tertiary loop responsible for heat rejection to the environment.

Figure 1: System Diagram of Westinghouse AP1000 Reactor



In the primary loop, pressurized light water circulates through the reactor vessel, absorbing thermal energy generated by nuclear fission. To prevent bulk boiling within the core, the system pressure is maintained at approximately 15.5 MPa. The heated coolant exits the reactor vessel via the hot leg and flows into the U-tubes of the Steam Generators. Here, thermal energy is transferred to the secondary fluid before the cooled primary water is pumped back to the reactor vessel via the cold leg to complete the loop.

The secondary loop functions as a regenerative Rankine cycle featuring moisture separation and reheating. Feedwater enters the shell side of the Steam Generator, where it absorbs heat from the primary loop to undergo a phase change into saturated steam at 5.76 MPa. This high-pressure steam expands through the High-Pressure (HP) turbine to generate mechanical work. A critical design feature of the AP1000 is the Moisture Separator Reheater (MSR) located between the turbine stages. The wet steam exiting the HP turbine is dried and reheated to a saturated vapor state before entering the Low-Pressure (LP) turbine. This process is essential to minimize liquid droplet formation during the final expansion stages, thereby protecting the turbine blades from erosion and improving overall cycle efficiency. The steam ultimately expands to the condenser pressure of 9.1 kPa.

Finally, the tertiary loop acts as the ultimate heat sink for the plant. Cooling water, drawn from a reservoir or cooling tower, circulates through the condenser tubes to absorb the latent heat of vaporization from the low-pressure steam, condensing it back into liquid water for recirculation by the feedwater pumps.

Governing Equations

The thermodynamic model was developed in Engineering Equation Solver (EES) using the IAPWS-IF97 property database. The system is analyzed under steady-state conditions, governed by the conservation of mass and the first and second laws of thermodynamics.

Mass and Energy Balance

For steady-flow components such as the turbines and pumps, the mass flow rate ($\dot{m}$) is constant, and the power output or input is determined by the enthalpy change across the component:

$$Wdot_{component} = mdot(h_{in} - h_{out})$$

Heat transfer in the Steam Generator and Condenser is modeled by an energy balance between the hot and cold fluid streams, assuming adiabatic boundaries:

Isentropic Efficiency

$$Qdot \ = \ mdot_{hot} \cdot \left(h_{hot,in} - h_{hot,out}\right) \ = \ mdot_{cold} \cdot \left(h_{cold,out} - h_{cold,in}\right)$$

Real-world irreversibilities in the turbomachinery are accounted for using isentropic efficiencies:

$$\eta_{turbine} = \frac{(h_{in} - h_{actual})}{(h_{in} - h_{ideal})}$$

Exergy Analysis

To quantify the quality of energy and identify system inefficiencies, the specific flow exergy (ψ) is calculated at each state point relative to the environmental dead state (T_0 =298.15 K, P_0 =101.3 kPa):

$$\psi = (h - h_o) - T_o \cdot (s - s_o)$$

The exergy destruction for any component is calculated by determining the difference between the exergy supplied and recovered, quantifying the lost work potential due to irreversibilities.

Design Parameters

Key design inputs were selected based on Westinghouse technical specifications and standard thermodynamic assumptions for gigawatt-class PWRs. These parameters, listed in Table 1, define the boundary conditions for the EES simulation.

Table 1: AP1000 Design Input Parameters

Parameter	**Value**	**Description**
Primary Side		
Primary Operating Pressure	15.5 MPa	Reactor Coolant System pressure to prevent boiling
Reactor Outlet Temperature ($Thot$)	321.1 °C	Temperature leaving the vessel
Reactor Inlet Temperature ($Tcold$)	280.7 °C	Temperature entering the vessel
Pump Isentropic Efficiency	85%	Assumed efficiency for primary coolant pumps
Secondary Side		
HP Turbine Inlet Pressure	5.76 MPa	Saturated steam pressure from SG

MSR Crossover Pressure	1.0 MPa	Intermediate pressure between HP and LP turbines
Condenser Pressure	9.1 kPa	Backpressure determined by cooling water limits
Turbine Isentropic Efficiency	88%	Assumed for both HP and LP stages
Tertiary Side		
Cooling Water Inlet Temp	30.5 °C	Ambient heat sink condition
Cooling Water ΔT	12 °C	Designed temperature rise across condenser

Design: GE-Hitachi BWRX-300 Reactor

System Description

The GE-Hitachi BWRX-300 is modeled as a direct-cycle boiling water reactor (BWR), in which steam generated within the reactor vessel is routed directly to the turbine-generator, without the use of intermediate steam generators. This simplified architecture described in the *GE-Hitachi BWRX-300 Technical Overview* (GEH, 2021) and with operating principles inherited from the ESBWR Design Control Document (DCD), which serves as the certified reference design for the BWRX-300 (NRC ESBWR DCD, Rev. 10). The system boundary for the BWRX-300 thermal-hydraulic model includes the four major energy generation subsystems.; the core and steam generation region, the three turbines (1 HP, 2 LP), the moisture separator and single stage reheater, and the condenser and heat-rejection loop. Excluded from the boundary include the containment, ECCS, ADS, control systems, reactivity control, balance-of-plant HVAC, and all electrical distribution beyond the generator terminals. This simplification aligns with the goal of generating physically consistent thermodynamic states to compare performance, exergy losses, condenser requirements, and sensitivities directly with the AP1000.

The BWRX-300 model operates with a fixed core thermal output of 870 MW_{th} at a vessel pressure of 7.2 MPa. Feedwater enters the core at approximately 312.7 K and is heated to 561 K as it flows through cylindrical fuel channel assemblies. The coolant is boiled in the core, generating a two-phase mixture. Unlike the AP1000, the BWRX-300, as modeled in figure 2, does not have U-tube steam generators. Instead, the reactor vessel serves as the boiler, and the primary radioactive loop is fed through the turbines, reducing parasitic loads.

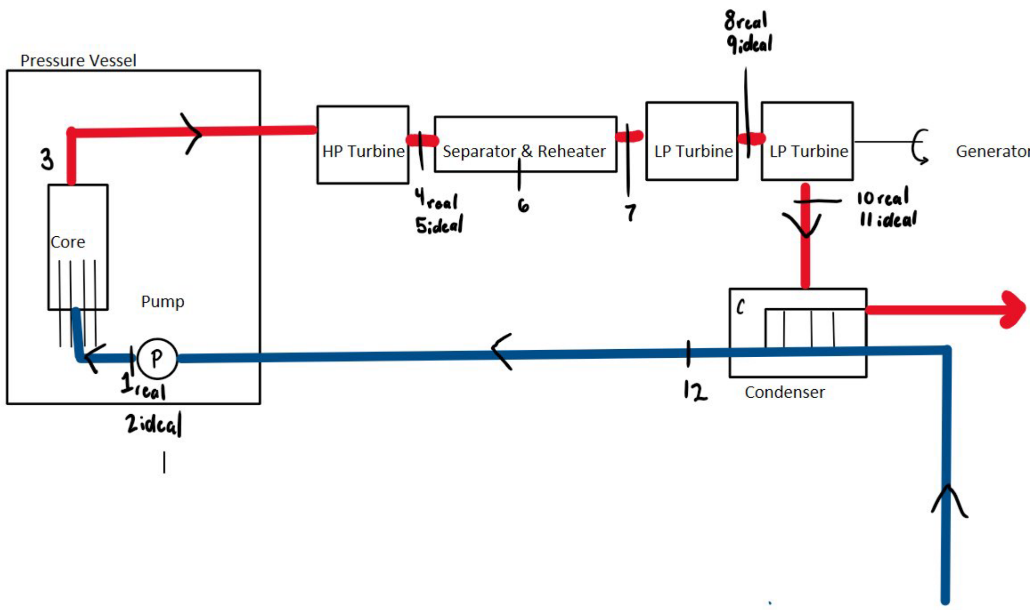


Figure 2: System Diagram of GE-Hitachi BWRX-300 Reactor

The direct cycle two-phase mixture enters the high-pressure turbine (HP) and expands to 1.7MPa with a target moisture fraction above 0.86 to protect turbine blades. An ideal moisture separator returns the steam to saturated vapor conditions before it enters a single reheat stage, where temperature is increased by 35 K to ensure near unity steam quality before entering downstream turbine stages. Both the AP1000 and the BWRX-300 employ a moisture separator reheater (MSR). The MSR reduces exergy destruction associated with wet expansion and mitigates blade corrosion.

The dual LP turbines expand the steam first to 250 kPa, where quality remains above 0.90, and then to the condenser pressure of 7 kPa, maintaining a minimum quality of 0.80 to limit erosion. The feedwater pump raises liquid from saturated conditions at 7 kPa back up to 7.2 MPa, operating at an 82% isentropic efficiency while overcoming minor piping losses. The condenser is sized to maintain a backpressure of 7 kPa, requiring a 10 K cooling-water temperature rise and an LMTD above 8 K to enable effective heat transfer. Generator efficiency is fixed at 98%, and a continuous 30 MW internal electrical load is applied to represent balance-of-plant consumption and auxiliary systems. The cycle is defined using vendor-consistent operating conditions for the BWRX-300. These are shown in Table 2.

Table 2: BWRX-300 Design Parameters and Set Points.

Parameter	Value
Reactor Thermal Power	**870 MW_{th}**
Reactor Pressure	**7.2 MPa**
Condenser Pressure	**7 kPa**
Core Inlet Temperature	**312.7 K**
Core Outlet Temperature	**561 K**
Reheat ΔT	**35 K**
HP Turbine Outlet Pressure	**1.7 MPa**
LP Turbine 1 Outlet Pressure	**250 kPa**
LP Turbine 2 Outlet Pressure	**7 kPa**
Generator Efficiency	**0.98**
Pump Isentropic Efficiency	**0.82**
HP Turbine Efficiency	**0.88**
LP Turbine Efficiencies	**0.90, 0.90**

Moisture Separator Efficiency	**1.0 (ideal)**

All thermodynamic states and cycle calculations were solved in EES using the IAPWS-IF97 water/steam property package

Assumptions

The BWRX-300 model applies several simplifying assumptions to isolate the thermodynamic behavior of the cycle. Operation is treated as perfectly steady-state at full power, with no transient behavior, load-following dynamics, or reactor-kinetics effects outside of the separate parametric analysis. Core heat deposition is assumed spatially uniform, and moisture separation is idealized, producing saturated vapor with no slip or entrainment. Pressure losses in the reactor vessel, steam lines, and feedwater piping are neglected except for pump-head calculations. The condenser is modeled as an ideal counterflow heat exchanger with constant cooling-water inlet temperature and no fouling (long-term degradation). Steam thermodynamic states are computed using equilibrium IAPWS-IF97 relations without two-phase slip modeling (since using equilibrium steam no need for liquid-vapor velocity difference). Nuclear safety systems, containment thermohydraulic, ECCS, and control-rod kinematics are excluded from the system boundary to focus exclusively on power-cycle performance. These assumptions are consistent with conceptual thermal-system modeling rather than detailed plant-scale simulation.

Governing Equations

The governing equations for the BWRX-300 EES modeling are as follows:

Mass Balance

$$\dot{m} = \frac{Qcore}{(h_3 - h_1)}$$

Isentropic Turbine Performance

$$h_{4s} = h(P_{4s}, s_3)$$

$$w_{HP} = \eta_{HP}(h_3 - h_{4s})$$

Pump Performance

$$w_{pump,ideal} = v_{12}(P_1 - P_{12})$$

$$w_{pump} = \frac{w_{pump,idea}}{\eta_{pump}}$$

Reheat Energy

$$Q_{reheat} = \dot{m}(h_7 - h_6)$$

Condenser Heat Rejection

$$Q_{cond} = \dot{m}(h_{10} - h_{12})$$

Exergy of Heat Input

$$Ex_{in} = Q\left(1 - \frac{T_0}{T}\right)$$

Electrical Output

$$W_{elec,net} = \eta_{gen} W_{net,mech} - W_{house}$$

Design Parameters

In the EES model, feedwater enters the reactor pressure vessel at 312.7 K and 7.2 MPa, where it is heated by the core until it reaches the steam-dome outlet at 561 K. The steam then expands through the high-pressure turbine to 1.7 MPa before passing through an ideal moisture separator. After separation, the steam is reheated by 35 K and sent to the first low-pressure turbine stage, expanding to 250 kPa. It then enters the second LP turbine and expands further to the 7 kPa condenser pressure. In the condenser, the steam fully condenses to saturated liquid at 312 K, and the feedwater pump raises it back to 7.2 MPa to close the loop. This flow path defines all thermodynamic states used in the EES model.

Nuclear Performance Parametric Analysis

To evaluate the performance of how feedwater mass flows through the core, impacts thermal performance and neutronics behavior of the BWRX-300. A parametric sweep of core mass flow was conducted from 50% to 150% of nominal. Feedwater enters the core at 7.2 MPa and 312.7 K, and for all cases the reactor thermal output was held constant at 870 MW_{th}. With a fixed core power, enthalpy rise scales inversely with flow rate. Reducing flow increases the temperature rise per unit mass, thus increasing outlet steam quality and void reactivity (moderation changes due to boiling). Thermal change drive negative reactivity feedback. Lower flow produces hotter fuel and higher void fractions, giving strong negative reactivity and subcritical k_eff values (a chain reaction will not occur to create energy). Increased pumping power and flow have the opposite effect, faster, cooler feedwater drives positive reactivity and a k_eff > 1 directly increasing predicted neutron production and core power if not controlled. Table 3 represents a fully coupled thermal–hydraulic and neutronic feedback picture of how recirculation flow influences core outlet temperature, steam quality, reactivity, multiplication factor, fission rate, and pumping power in a BWR-type core.

Table 3. BWRX-300 Thermal–Hydraulic + Neutronic Feedback with Pumping Penalty

Flow (×)	ṁ (kg/s)	T_out (K)	x_out	k_eff	Q_core (MW)	Pump Power (MW)
0.50	167.4	1143.9	1.000	0.9913	862.4	0.369
0.62	209.3	908.7	1.000	0.9948	865.5	0.721
0.75	251.2	751.8	1.000	0.9971	867.5	1.247
0.88	293.0	639.8	1.000	0.9988	869.0	1.980
1.00	334.9	561.2	0.984	1.0000	870.0	2.955
1.12	376.8	561.2	0.795	1.0000	870.0	4.208
1.25	418.6	561.2	0.643	1.0000	870.0	5.772
1.38	460.5	561.2	0.519	1.0121	880.5	7.682
1.50	502.3	561.2	0.416	1.0276	894.0	9.974

Data Center Design

The AP-1000 and BWRX-300 were modeled in combination with a full-scale data center model. Due to the lack of readily available data on component level parts within location specific data centers, several assumptions were utilized.

Per electricity panel, the average hyperscale data center ranges between 20 to 100 MW. The range is attributed to the variety of data center cooling applications (air cooling, liquid-to-chip, immersion cooling). Due to the progressive trend toward full scale liquid-to-chip cooling operations across the country, 100 MW power per data center was assumed.

Additionally, the PUE must also be considered. PUE is representative of the power usage effectiveness of the system. This refers to the contrast between the power consumption of all equipment in the Data Center from actual power consumption of the grid. A PUE of 1 would represent a perfect system, however; all data centers do possess higher PUE's. Due to the lack of resources on component level systems in data centers as previously mentioned, a PUE of 1.2 was assumed.

As a result, the total electricity consumption of a standard 100 MW, liquid-to-chip, data center can be found using the following equation in MWh:

$$Total\,Electricity\,Consumption = Total\,Power\,Draw\,(MW) \cdot PUE \cdot 8760$$

In addition to the 100 MW data center design for power plant analysis, a 42 MW liquid-to-chip cooling loop was additionally modeled from primary to secondary loop.

The primary loop is representative of the chiller loop. In the design of the 42 MW cooling loop, 26 York-YVAA-500 chillers were modeled. 26 chillers are representative of an N+2 system. This ensures full loop capacity with two chiller failures. Thus, under normal operating conditions, 24 chillers are run at full capacity. The Table 4 represents the gathered data of the chiller loop:

Table 4. Primary Chiller Loop Design Parameters

Parameter	Value
Total Number of Chillers (N+2)	**26**

Running Chillers Under Normal Operation (N)	**24**
Chiller Flow Rate	**1149 GPM**
Primary Loop Pipe Size	**24 in.**
Total Pipe Length	**560 ft**
# of Segmentation valves	**25**
# of Bends	**4**

With an N+2 arrangement in the chiller loop, segmentation valves must be placed between every chiller. This ensures only two chillers go down during a segmentation valve failure, thus providing an N system. As a result, there are 25 segmentation valves in the primary loop design.

Four pipe diameters must be between every chiller to ensure proper flow readings by an inline velocity flow meter. As a result, the following equations represent the calculation for pipe length:

$$Pipe\ \text{Length} = 2 \cdot \left((4 \cdot Pipe\ Diameter \cdot 25 + 80\ (assumed\ number\ for\ side\ length\ )\right)$$

The accumulation of the pipe lengths, segmentation valves, and bends contributes to a head loss in the primary loop system. The following detail the governing equations to size a pump that allows for consistent flow rate throughout the primary loop system:

Bernoulli: $P_1 + .5\rho V_1^2 \ + \rho g z_1 \ = P_2 + .5\rho V_2^2 \ + \rho g z_2 \ + H_L$

Major Head Loss: $H_{L,Maj} \ = \ f \cdot \frac{L}{D} \cdot \frac{V^2}{2g}$

Minor Head Loss: $H_{L,\,Min} \ = \ K \cdot \frac{V^2}{2g}$

Haaland Equation: $f = \frac{.3086}{\left\{\log\left(\frac{6.9}{Re}+\left(\frac{\varepsilon}{3.7D}\right)^{1.11}\right)\right\}^2}$

Pump Horsepower: $Hp \ = \ \frac{(Q \cdot H_L \cdot SG)}{3960 \cdot n_{pump}}$

As previously mentioned, the primary chiller loop provides chilled water to the secondary loop. The heat exchange occurs at the selected Liebert XDU-1350. This allows the primary loop fluid to extract heat away from the secondary loop.

The Liebert XDU-1350 follows a brazed plate heat exchanger model with a variable number of plates. Table 5 lists the values given from the Liebert XDU-1350 manual and industry standard:

Table 5. Given Liebert XDU-1350 Temperature State Points

Parameter	Value
Heat Transfer Rate	**1350 kW**
Chiller Supply Temperature	**44 F**
Chiller Return Temperature	**54 F**
Secondary Loop Inlet Temperature	**52 F**
Secondary Loop Outlet Temperature	**70 F**

With respect to the specifications given regarding the Liebert XDU heat exchange method, a brazen plate heat transfer analysis was chosen. The following detail the governing equations to obtain the length of the brazen plate heat exchanger:

$$LMTD = \frac{(\Delta T_{primary} - \Delta T_{secondary})}{Ln\left(\frac{(\Delta T_{primary})}{\Delta T_{secondary}}\right)}$$

$$UA_{required} = \frac{Qdot}{LMTD}$$

Mass Flux: $G = \frac{mdot}{Flow\ Area \cdot 3600}$

Reynold's Number: $Re = \frac{(G \cdot Hydraulic\ Diameter)}{\mu}$

Nusselt's Number: $Nu = .2 \cdot Re$^{.67} $\cdot$ Pr ^{.4}

$$\text{Heat Transfer Coefficient: } h = \frac{(Nu \cdot k)}{Hydraulic\ Diameter}$$

$$\text{U} = U = \frac{1}{\left(\frac{1}{h_{primary}} + \frac{1}{h_{\sec ondary}}\right)}$$

In the governing equations, primary represents the fluid that is being supplied from the chiller. Secondary represents the fluid that is being supplied through the cold plates. The primary fluid is a 25% propylene glycol solution, and the secondary fluid is 30% propylene glycol solution. This defines the fluid property throughout the model.

Analysis and Results: AP1000

Thermodynamic Performance

The simulation results characterize the AP1000 as a massive baseload generator capable of delivering consistent power well in excess of specific facility requirements (Table 6). The plant generates a net electrical output of 1,224 MW, derived from a reactor thermal power of 3,378 MW. This results in an overall first-law thermal efficiency of 36.24%, which aligns with the industry standard for modern light water reactors. The slight deviation from the rated 3,415 MW thermal power is attributed to the specific enthalpy drops calculated via the IAPWS-IF97 water properties at the precise temperature inputs provided.

The scale of the AP1000 is further highlighted by the mass flow requirements. The secondary loop demands a steam flow rate of 1,886 kg/s to achieve the gigawatt-scale output. Consequently, the heat rejection requirement places a significant burden on the tertiary loop, necessitating a cooling water flow rate of nearly 50,000 kg/s. This magnitude of water consumption dictates that such a facility must be sited near a major body of water or utilize extensive cooling tower infrastructure.

Table 6. AP1000 Cycle Performance Outputs

Output Parameter	Value	Implications
Reactor Thermal Power	**3,378 MW**	Matches rated core power (3400 MW)
Net Electrical Output	**1,224 MW**	**12x larger** than the Data Center demand
Overall Thermal Efficiency	**36.24%**	Indicates efficient fuel utilization
Exergetic Efficiency	**40.24%**	Measures 2nd Law performance
Steam Mass Flow Rate	**1,886 kg/s**	High flow required for gigawatt-scale output
Cooling Water Flow Rate	**49,696 kg/s**	Massive water requirement for heat rejection
Total Exergy Destruction	**1,922 MW**	Total lost work potential

State Points and Array Table

The thermodynamic output from the EES model of the working fluid is captured in the Array Table 7. This array maps the cycle index (1 through 8) to physical properties, facilitating the generation of the Temperature-Entropy (T-s) diagram. A sequential review of these indices reveals the specific thermodynamic functions of the loop components.

The process begins at Index 1, where high quality steam enters the High Pressure turbine at 5.76 MPa and 272.9°C. The expansion to Index 2 (1.0 MPa) extracts the initial stage of work but drops the steam quality to 0.87. This state point is critical; without intervention, further expansion would lead to destructive erosion of the turbine blades. The transition from Index 2 to Index 3 represents the Moisture Separator Reheater (MSR). Here, the model shows an increase in entropy and enthalpy at constant pressure, verifying that the steam has been dried and reheated to a saturated vapor state before entering the low pressure stages.

The final expansion to the condenser pressure occurs between Index 3 and Index 4. The Array Table indicates a final exhaust quality of 0.824 at Index 4. While this moisture content is high compared to fossil fuel superheated cycles, it is characteristic of nuclear saturated steam cycles and necessitates the use of erosion resistant blade materials in the final turbine stages. The loop is closed through the pumping stages (Indices 5 through 8), where the fluid is pressurized from

9.1 kPa back to 5.76 MPa. The slight temperature rise observed between Index 6 and Index 7 confirms the preheating effect of the Open Feedwater Heater, which regenerates energy that would otherwise be lost to the condenser.

Table 7. Thermodynamic Array Data (Secondary Loop)

Array Index	Location	P [kPa]	T [°C]	h [kJ/kg]	s [kJ/kg-K]	x [-]
[1]	HP Turbine Inlet	5,760	272.9	2,787	5.909	1.0
[2]	HP Turbine Outlet	1,000	179.9	2,509	5.993	0.87
[3]	LP Turbine Inlet	1,000	179.9	2,777	6.585	1.0
[4]	LP Turbine Outlet	9.1	43.97	2,159	6.851	0.82
[5]	Condenser Outlet	9.1	43.97	184.1	0.625	0.0
[6]	Condensate Pump	1,000	44.05	185.3	0.626	-
[7]	FWH Outlet	1,000	179.9	762.5	2.138	-
[8]	SG Inlet	5,760	180.8	768.8	2.14	-

Exergy Analysis and Destruction

The Second Law analysis provides deeper insight into the system's inefficiencies by quantifying exergy destruction. As shown in Table 8, the total exergy destruction for the plant is 1,922 MW. The reactor core is the dominant source of irreversibility, accounting for 73.5% of the total destruction. This large loss is inherent to the fission process, where energy is released at extremely high temperatures but transferred to the coolant across a significant temperature gradient.

The Steam Generator contributes another 6.7% of the total destruction, driven by the temperature difference between the primary coolant (321°C) and the secondary steam (272°C). In contrast, the turbomachinery is relatively efficient, with the combined HP and LP turbines accounting for only 7.4% of the total exergy destruction. This distribution indicates that while component improvements (such as more efficient turbines) offer marginal gains, the thermodynamic ceiling is largely set by the reactor core and heat transfer constraints.

Table 8. Exergy Destruction by Component

Component	Exergy Destruction [MW]	% of Total Destruction
Reactor Core	1,412	73.5%
Steam Generator	128.1	6.7%
LP Turbine	100.1	5.2%
Condenser	56.6	2.9%
HP Turbine	41.9	2.2%
Total Losses	**1,922**	**100%**

Parametric Analysis

To fully characterize the operational envelope of the AP1000, four distinct parametric studies were conducted. These analyses investigate environmental sensitivity, cycle design optimization, component degradation, and thermodynamic theoretical limits.

Environmental Impact (Seasonality)

The first parametric study evaluates the plant's sensitivity to the condenser pressure (P_{cond}), which is directly driven by the environmental cooling water temperature. Because a nuclear plant operates as a heat engine, its efficiency is strictly bounded by the temperature of its cold reservoir. The analysis (Table 9) varies the condenser pressure from 5 kPa (deep winter) to 15 kPa (hot summer).

As pressure rises, the net power output drops significantly, from a peak of 1,282 MW at 5 kPa to 1,172 MW at 15 kPa. This seasonal derating of 110 MW represents a nearly 9% swing in generation capacity. Simultaneously, the overall thermal efficiency drops from 37.95% to 34.69%. In the context of the data center, this "lost" 110 MW is equivalent to the entire electrical load of the facility. This finding highlights a critical risk for data center integration: the power source is least efficient exactly when the data center cooling load is highest (during summer months). Additionally, exergy efficiency drops from 42.14% to 38.52%, and total exergy losses rise by over 100 MW, confirming that operating at higher backpressures wastes significant work potential.

Table 9. Sensitivity of AP1000 to Environmental Pressure Conditions

P_{cond}	$Wdot_{net,model}$	$\eta_{th,overall}$	x_{S4}	$Ex_{total,losses}$	$\eta_{exergy,pct}$
5	1282	0.3795	0.8097	1862	42.14
6	1265	0.3745	0.8139	1880	41.58
7	1250	0.3701	0.8175	1895	41.09
8	1237	0.3662	0.8207	1909	40.66
9	1225	0.3628	0.8236	1921	40.28
10	1215	0.3596	0.8262	1932	39.93
11	1205	0.3567	0.8286	1942	39.6
12	1196	0.354	0.8308	1952	39.31
13	1187	0.3515	0.8328	1961	39.03
14	1179	0.3491	0.8347	1969	38.77
15	1172	0.3469	0.8365	1977	38.52

Feedwater Heater Optimization

The second parametric analysis investigated the optimal crossover pressure ($P_{crossover}$) for the Open Feedwater Heater (OFWH). The OFWH improves cycle efficiency by utilizing steam extracted from the turbine to preheat the feedwater, but this comes at the cost of reducing the mass flow rate through the low-pressure turbine. By varying the crossover pressure from 500 kPa to 2000 kPa, the model identified a thermodynamic "sweet spot."

Table 10 shows that net power and efficiency peak at a crossover pressure of 500 kPa, achieving 1,235 MW and 36.57% efficiency. As the crossover pressure increases to 2000 kPa, the bleed fraction (y) rises from 20.4% to nearly 30%, diverting too much steam from the LP turbine. Consequently, net power drops to 1,188 MW. This suggests that the baseline design pressure of 1,000 kPa, while robust, sacrifices approximately 13 MW of potential output compared to a lower-pressure optimization.

Table 10. AP1000 Feedwater Pressure Optimization

$P_{crossover}$	$\eta_{th,overall}$	y	$Wdot_{net,model}$	$Ex_{total,losses}$	$\eta_{exergy,pct}$
500	0.3657	0.2044	1235	1922	40.61
650	0.3652	0.2206	1234	1921	40.55
800	0.3642	0.2338	1230	1921	40.44
950	0.3629	0.245	1226	1922	40.29
1100	0.3614	0.2548	1221	1923	40.13
1250	0.3599	0.2636	1216	1924	39.96
1400	0.3583	0.2715	1210	1926	39.78
1550	0.3566	0.2787	1205	1928	39.6
1700	0.355	0.2854	1199	1930	39.41
1850	0.3533	0.2916	1193	1932	39.22
2000	0.3515	0.2975	1188	1934	39.03

Turbine Aging and Reliability

The third study simulated the effects of mechanical degradation by varying the isentropic efficiency ($\eta_{t,HP}$) of the high pressure turbine from 0.90 down to 0.50 (Table 11). This simulates severe long term wear, such as blade pitting, seal leakage, and increased surface roughness.

The analysis shows a linear relationship between component health and plant output. Dropping the turbine efficiency from 0.90 to 0.50 causes the net power output to plummet from 1,234 MW to 1,035 MW, a loss of nearly 200 MW. Exergy efficiency similarly falls from 40.57% to 34.03%. The exergy analysis reveals that as the turbine degrades, the total exergy losses ($Ex_{total,losses}$) rise from 1,915 MW to 2,060 MW. This confirms that the lost work does not simply disappear; it is converted into internal heating (irreversibility), which ultimately places a larger heat load on the condenser and the cooling water system ($Q_{out,model}$) rises from 2490 MW to 2533 MW). This implies that as the plant ages, not only does revenue decrease due to lower power output, but the heat rejected to the environment actually increases.

Table 11. AP1000 Sensitivity to Turbine Isentropic Efficiency

$\eta_{t,HP}$	$\eta_{th,overall}$	$Wdot_{net,model}$	$Qdot_{out,model}$	$\eta_{exergy,pct}$	$Ex_{total,losses}$
.9	0.3654	1234	2490	40.57	1915
.86	0.3595	1214	2495	39.92	1929
.82	0.3536	1195	2499	39.26	1944
,78	0.3477	1175	2503	38.61	1959
.74	0.3418	1155	2508	37.96	1973
.7	0.336	1135	2516	37.3	1988
.66	0.3301	1115	2520	36.65	2002
.62	0.3242	1095	2525	35.99	2017
.58	0.3183	1075	2529	35.34	2031
.54	0.3124	1055	2529	34.68	2046
.5	0.3064	1035	2533	34.03	2060

Dead State Sensitivity (T_0)

The final parametric study examined the theoretical influence of the "Dead State" temperature (T_0) on the exergy balance. By varying T_0 from 5°C to 50°C while holding the plant operation constant, we analyzed the change in the theoretical availability of the fuel.

Thermodynamically, a lower dead state temperature increases the Carnot limit, meaning the fuel has a higher *potential* to do work. Table 12 confirms this: as T_0 drops from 50°C to 5°C, the total exergy input ($E_{xin,total}$) rises from 3,014 MW to 3,065 MW. However, the simulation reveals a counter-intuitive result: the plant's net exergy efficiency ($\eta_{exergy,pct}$) actually decreases slightly as the dead state temperature drops (from 40.62% to 39.95%). This occurs because the plant design is fixed; it cannot lower its condenser pressure infinitely to match the dropping T_0.

Therefore, while the potential for work increases in the winter, the plant is unable to capture that extra potential, leading to a larger calculated gap (Total Losses rise from 1,875 MW to 1,960 MW) between the theoretical maximum and the actual output. This underscores the difference between theoretical thermodynamic availability and the practical engineering limits of a fixed-design power plant.

Table 12. Dead State Temperature Influence on Exergy Balance

To_c	$Ex_{in,total}$	$Ex_{loss,env}$	$Ex_{total,losses}$	$\eta_{exergy,pct}$
5	3065	253.5	1960	39.95
9.5	3060	217.3	1951	40.01
14	3055	181.1	1943	40.08
18.5	3050	144.9	1934	40.15
23	3045	108.7	1926	40.21
27.5	3040	72.44	1917	40.28
33	3035	36.22	1909	40.35
36.5	3029	0	1901	40.41
41	3024	-36.22	1892	40.48
45.5	3019	-72.44	1884	40.55
50	3014	-108.7	1875	40.62

Analysis and Results: BWRX-300

Thermodynamic Performance

The modeled BWRX-300, simplified and modeled in ees, performs as a direct-cycle reactor optimized for moderate-scale power delivery. With a reactor thermal output of 870 MW_{th}, the plant produces a net electrical output of 293.9 MW, consistent with GE-Hitachi's advertised 300 MWe nameplate. The first-law thermal efficiency generated from ees is 33.49%, this value aligns with typical saturated-steam nuclear Rankine cycles (32–34%).

This section presents the thermodynamic and exergy results for the modeled BWRX-300 boiling water reactor power cycle (Table 13). All values originate directly from the EES simulation and represent a steady-state plant operating at 870 MW_{th}, with a reactor pressure of 7.2 MPa, and single-reheat Rankine configuration. The working fluid is modeled using IAPWS steam properties.

Compared to the AP1000 the direct-cycle architecture reduces requirements, for example the BWRX-300 requires a steam mass flow of 334.8 kg/s, nearly one-sixth of the AP1000 steam requirement (1,886 kg/s). This reduces the environmental requirements for the SMR, as the BWRX-300 can obtain its cooling water from standard mechanical-draft cooling towers or small-scale local water sources, meaning large coolant streams are not diverted from local ecosystems at magnitudes that cause significant damage. Consequently, condenser, pump work, and cooling-water demands are also reduced.

Table 13. BWRX-300 Cycle Performance Outputs

Output Parameter	**Value**	**Implications**
Reactor Thermal Power	**870 MW_{th}**	GE-Hitachi's rated thermal output for the BWRX-300
Net Electrical Output	**293.9 MW**	Sized appropriately for a single hyperscale data center (≈100 MW)
Overall Thermal Efficiency	**33.49%**	Typical for saturated-steam BWRs; slightly lower than PWR superheated cycles
Exergy Efficiency	**64.69%**	High due to direct cycle; low irreversibility compared to indirect PWR cycles
Steam Mass Flow Rate	**334.8 kg/s**	Low steam requirement reduces turbine size and balance-of-plant complexity
Cooling Water Flow Rate	**15,701 kg/s**	Lowered flow constraints compared to AP1000
Total Turbine Work	**333.4 MW**	Turbine metrics aligned for ~300 MWe class machine
Pump Work	**3.0 MW**	Small pumping requirements due to single-loop BWR configuration

State Points and Array Table

The thermodynamic state array states 1 through 12) traces the complete path of coolant and steam through the BWRD-300 direct-cycle configuration. The ees model outputs the Temperature-Entropy (T-s) diagram (Figure 3).

Figure 3: T-s Plot of BWRX-300 State Points

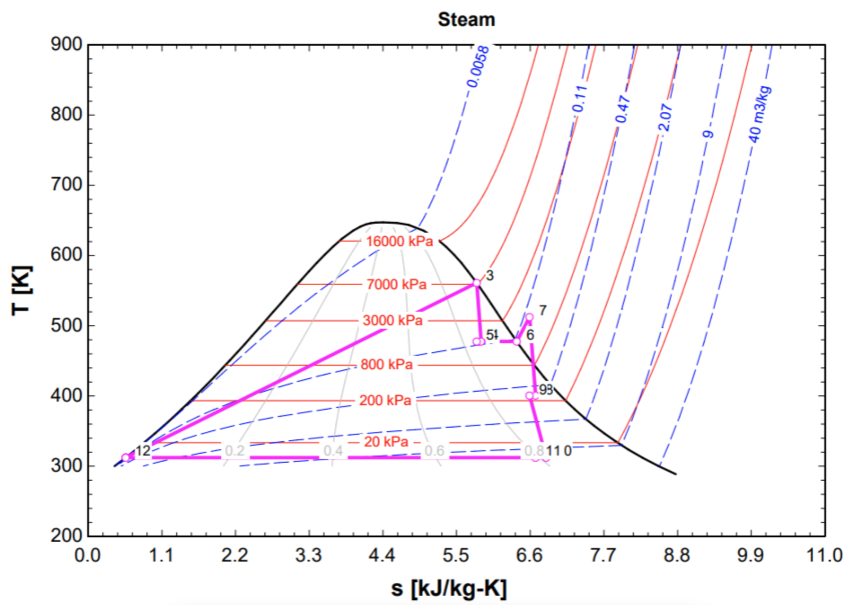


Table X summarizes the pressure, temperature, enthalpy, entropy, specific exergy, and quality at each state point. These values demonstrate proper closure of the Rankine cycle with a first-law residual of -5.68×10⁻¹⁴ kW, confirming energy conservation. The table confirms several expected features of a boiling water reactor (BWR) cycle, validating core performance, saturated expansion across three turbine stages, and moisture-removal systems.

The cycle begins as feedwater is driven through the reactor core at state 1 (Table 14). Feedwater enters the core at 312.7 K and 7.2 MPa and exits as saturated-to-slightly-superheated steam at 561 K, consistent with public GE-Hitachi documentation for the BWRX-300. The enthalpy rise across the core (172.2 to 2771 kJ/kg) corresponds to the required 870 MWth thermal output when paired with the computed mass flow rate. State 3 to 4 represents the high-pressure turbine expansion, where steam expands to 1.7 MPa, reaching a quality of ~0.868, typical of saturated expansion in BWR high-pressure stages. The specific exergy drop matches the mechanical work produced by the HP turbine when efficiency is applied.

Moisture separation and reheat are represented by both State 6 and State 7. State 4 is equal to state 6 because the model uses an ideal separator, and the liquid of the two-phase mixture is removed before the steam enters the turbine. From state 6 to 7, reheat raises steam back to 512.5

K, adding deltaT = 35 K above saturation, as is standard for BWR moisture-removal reheating systems.

Low pressure turbine expansion is represented by state 8 and state 10. From state 7 to 8, flow expands to 250 kPa, reaching a quality of 0.9315, showing a realistic wet-steam condition for an LP stage. From state 8 to 10, final expansion to 7 kPa produces x = 0.8138, well within expected condenser-inlet quality ranges (0.80–0.85).

The condenser is represented by state 12. From state 10 to 12, the condenser returns the flow to saturated liquid at 7 kPa. Then from state 12 to 1, pumping raises the pressure back to 7.2 MPa, and the coolant is recirculated back through the core. Pumping increases enthalpy modestly from 163 to 172 kJ/kg, confirming physically correct liquid-pump behavior undergoing work input.

The mass flow rate found through EES is 334.8 kg/s which matches General Electric's published nominal BWRX-300 core steam flow of 330–360 kg/s.

Turbine and pump work are summarized in Table 15. The cycle produces 333.4 $MW_{me}c_{h}$ of turbine work and consumes only ~3 MW of pumping power, confirming correct Rankine-cycle behavior for a system of this scale.

Overall, the state-point sequence confirms that the BWRX-300 model reproduces the expected thermal, phase-change, and turbine-stage transitions of a modern boiling water reactor, with realistic steam qualities, turbine inlet and outlet conditions, and a physically consistent Rankine-cycle closure.

Table 14. Thermodynamic Array Data (Direct/Primary Loop)

Array Index	**Location**	**P [kPa]**	**T [°C]**	**h [kJ/kg]**	**s [kJ/kg-K]**	**x [-]**
[1]	Core Inlet / Feedwater	7200	39.5°C	172.2	0.5642	0
[3]	Core Outlet / Steam Dome	7200	287.9°C	2771	5.801	1.0
[4]	HP Turbine Outlet	1700	204.4°C	2541	5.867	0.8681

[6]	Moisture Separator Outlet (same as State 4)	1700	204.4°C	2541	5.867	0.8681
[7]	Reheat Outlet / LP Turbine Inlet	1700	239.4°C	2889	6.59	1.0
[8]	LP1 Turbine Outlet	250	127.5°C	2567	6.68	0.9315
[10]	LP2 Turbine Outlet / Condenser Inlet	7	39.0°C	2123	6.838	0.8138
[12]	Condenser Outlet / Pump Inlet	7	39.0°C	163.4	0.559	0

Table 15: BWRX-300 Turbine Work and Pump Work

Component	**Mechanical Work (kW)**
HP Turbine	76,905
LP1 Turbine	107,893
LP2 Turbine	148,637
Total Turbine Work	**333,435**
Pump Work	2,959

Upon applying generator efficiency and house electrical load (30 MW), Gross Electrical Output is found to be 323.9 MW and Net Electrical Output to be 293.9 MW. GE-Hitachi advertises 300 MWe net; EES value 293.9 MWe accounts for house loads.

The condenser rejects 656,203 kW (656 MW) of heat; 656 MW of heat must be removed by the condenser which is consistent with a 33–34% thermal efficiency plant. The EES model output aa thermal efficiency of 33.49%. The tertiary (cooling)loop is where the 656 MW of heat is rejected to by condenser. Using a temperature rise of 10 K, the cooling water mass flow is calculated to be 15,701 kg/s, volumetric flow to be 15.8 m^3/s, and inlet to outlet temperatures to be 303 K to 313 K.

The BWRX-300 state points reflect the fundamental design logic of a small modular boiling water reactor. High pressure in the core maintains stable boiling; moderate steam qualities protect turbine blades from corrosion, and staged pressure drops extract work efficiently. The direct production of near saturated steam by the core eliminates the need for steam generators.

Exergy Analysis and Destruction

A second law analysis reveals insights into the BWRX-300's optimized systems performance, compared to the AP1000. The exergy efficiency calculated is 64.69%, which falls within the 60-70% range for typical BWR nuclear plants. Looking at dominant losses listed in Table X, the reactor core and the condenser make up most of the loss. The reactor core contributes the largest irreversibility (≈60 MW), as expected due to nuclear heat transfer across finite temperature differences. The condenser is the single largest thermodynamic loss mechanism (≈30 MW exergy destroyed), inherent to all Rankine cycles. The turbine stages are efficient and destroy relatively little exergy. House loads (≈30 MW) appear as an exergy sink. The EES model outputs an Exergy Balance Residual as a check value, it output −2.84×10^-14 (~0 and confirms model consistency). The exergy inputs and losses quantify the irreversibility's in each major component and are shown in Table 16. The exergy destruction is presented in Table 17.

Table 16. BWRX-300 Exergy Inputs

Source	Exergy (kW)
Reactor Heat	407,861
Reheat Source	46,430
Total Exergy In	**454,291**

Table 17. BWRX-300 Exergy Destruction by Component

Component	Exergy Destruction [MW]	% of Total Destruction
Reactor Core	60.43	37.67%
HP Turbine	6.55	4.08%
LP1 Turbine	8.92	5.56%
LP2 Turbine	15.77	9.82%
Pump	0.51	0.32%
Condenser	29.75	18.54%
Reheater	1.90	1.19%
Generator	6.61	4.12%
House Load	30.00	18.70%
TOTAL	**160.42**	**100%**

The 64.69% exergy efficiency indicates that approximately 35% of the available work potential is destroyed through irreversibility's, typical for thermal power cycles operating between these temperature limits. The key cycle performance outputs are shown in Table 18.

Table 18. Summary of Key BWRXX-300 EES Outputs

Output Parameter	Value
Mass flow rate of steam	334.8 kg/s
Total turbine work	333.4 MW
Pump work	3.0 MW
Gross electrical output	323.9 MW

Net electrical output	293.9 MW
Thermal efficiency	33.49%
Exergy efficiency	64.69%
Condenser heat rejected	656 MW
Cooling-water mass flow	15,701 kg/s

Overall, the BWRX-300 model consistently reproduces the expected performance of a modern boiling water reactor. Compared with the AP1000, without the additional losses and temperature gradient driven by the steam generator, the BWRX-300 reduces thermal irreversibility. The exergy efficiency boost from a direct cycle is limited by the tightened conditions of core and inlet conditions. Since the AP1000 expands across a higher total enthalpy drop, the absolute turbine's exergy loss is larger, but the per-MW turbine efficiency is roughly equal across both systems. BWRX-300 condenser losses are a larger fraction of total work potential than in AP1000. The mass flow rate, outlet temperature, turbine work, and condenser load all fall within vendor-published values, indicating that the thermodynamic cycle is correctly sized. The net electrical output of 293.9 MWe aligns with GE-Hitachi's advertised 300 MWe rating once a 30 MW house load is included. A thermal efficiency of 33.5% and exergy efficiency of 64.7% are typical for light-water reactors, with most of the exergy destruction occurring in the reactor core and condenser. The low pump power requirement (~3 MW) and realistic steam qualities at each turbine stage further confirm physical consistency. Overall, the results indicate that the modeled BWRX-300 cycle is thermodynamically valid and suitable for downstream comparison to a PWR and to the data-center cooling demand.

Parametric Analysis

To fully characterize the operational envelope for the BWRX-300 compared to the AP1000, three distinct parametric studies were conducted. These analyses investigate environmental sensitivity, cycle thermal optimization, and thermodynamic theoretical limits.

Environmental Impact (Seasonality)

The first parametric study evaluates performance as a function of environmental operating conditions. The parametric analysis of condenser pressure outlines the trend of the BWRX-300 cycle as a response to the quality of the heat sink environment (Table 19). As P_cond increases from 5 to 14 kPa, the condenser saturation temperature increases; therefore, the steam cannot fully reject heat. The PR available to the LP turbine is thus reduced, decreasing the net electrical output (301,748 kW at 5 kPa to 276,406 kW at 14 kPa). Plant net thermal efficiency ≈30.6% at the lowest condenser pressure and falls to ≈27.9% at the highest. The exergy destruction in the condenser (Ex_dest,cond) increases with pressure, indicating that irreversibility grows as the condenser operates at warmer temperatures. The exergy loss to the environment (Ex_loss,cond) nearly doubles across the analysis, demonstrating that the work potential of the reactor is rejected as low-grade heat with greater sensitivity to higher condenser pressures compared to the AP1000. These trends indicate that both nuclear systems' performances directly rely on the ambient pressure and temperature conditions, with the small-scale BWRX-300 resulting in larger percentage swings in output when environmental or operational conditions change.

Table1 9. Sensitivity of BWRX-300 to Environmental Pressure Conditions

P_{cond}	$W_{elec,net}$	$Ex_{dest,cond}$	$Ex_{loss,cond}$	$\eta_{plant,net,pct}$
5	301748	-0.01986	16966	30.62
6	297523	0.4213	23836	30.17
7	293867	0.7642	29745	29.78
8	290636	1.032	34939	29.44
9	287736	1.242	39583	29.14
10	285100	1.408	43786	28.86
11	282681	1.538	47629	28.6
12	280443	1.639	51173	28.37
13	278358	1.718	54464	28.15
14	276406	1.779	57537	27.94

Core Outlet Thermal Optimization

In accordance with the nuclear core performance metrics, varying the reactor core outlet temperature impacts the flow rate of steam required and the overall cycle efficiency (Table 20). As T increases from 545 K to 590 K, the enthalpy rise across the core increases, resulting in a sharp drop in the required mass flow rate. The mass flow rate falls from 851 kg/s at 545 K to ≈319 kg/s at 590 K. In this parametric analysis, we assume a fixed thermal power, so if the core outlet steam has an increased thermal energy, the density of the steam must decrease. Thermal efficiency increases from about 28.5% to nearly 33.9%, and plant net efficiency increases from ≈26.7% to ≈30.1% across the sweep. Despite this, net electrical output remains fairly constant, with a small change resulting from the reduced mass flow, offsetting the higher specific turbine work. Overall, operating at higher reactor outlet temperatures improves cycle efficiency and reduces required mass flow/pumping requirements, both of which are advantageous. However, the marginal gains diminish at the highest temperatures, indicating realistic performance limits.

Table 20. Flow Rate and BWRX-300 Efficiency Sensitivity to Core Outlet Temperatures

$Tcoreout$	$mdot_{steam}$	$W_{elec,net}$	$\eta_{thermal,pct}$	$\eta_{plant,net,pct}$	$\eta_{exergy,pct}$
545	851.3	622036	28.51	26.65	63.69
550	830.3	608341	28.58	26.7	63.42
555	810	595219	28.67	26.75	63.17
560	790.3	582618	28.75	26.8	62.92
565	332.1	292191	33.56	29.82	64.25
570	329.1	290336	33.63	29.87	63.71
575	326.3	288685	33.71	29.92	63.19
580	323.8	287198	33.78	29.97	62.69
585	321.4	285847	33.85	30.02	62.21
590	319.1	284610	33.92	30.07	61.74

Turbine Aging and Reheating

By increasing the reheat temperature difference, the steam achieves a dryer state before entering the turbine, improving the performance of the LP turbines. As ΔTreheat increases from 1 K to 50 K, quality rises from about 0.8966 to 0.9449 at the first LP turbine outlet and from 0.7884 to 0.8235 at the second LP turbine outlet. Reheat improves each turbine's lifespan and increases the available enthalpy drop in the LP turbines. The trend observed is that by introducing a larger research temperature difference, the cycle can extract more useful work, increasing net electrical output from 283.7 MW at 1 K of reheat to 298.3 MW at 50 K (Table 21). Exergy destruction in the LP turbines increases, while exergy destruction in the reheater increases as supplying larger thermal flux is more irreversible. Overall, the data shows that increasing the reheat temperature difference steadily improves steam quality, turbine performance, and net electrical output for the

BWRX-300 cycle. Within the range studied (1–50 K), higher reheat temperatures consistently benefit the system, and no practical upper limit is reached.

Table 21. Turbine Aging and Reheating Impact on BWRX-300

$Treheat$	$x8$	$x10$	$W_{elec,net}$	$\eta_{plant,net,pct}$	$Ex_{dest,LP1}$	$Ex_{dest,LP2}$	$Ex_{dest,reheat}$
1	0.8966	0.7884	283738	29.68	8483	15229	55.1
10	0.9067	0.7958	286490	29.7	8594	15385	550
20	0.9171	0.9033	289461	29.73	8720	15545	1094
25	0.922	0.8069	290932	29,74	8785	15621	1364
30	0.9268	0.8104	292400	29.76	8851	15695	1634
35	0.9315	0.8138	293867	29.78	8919	15767	1902
40	0.9361	0.9171	295334	29.81	8988	15837	2170
50	0.9449	0.8235	298277	29.86	9130	15973	2705

Data Center Analysis

As previously mentioned, in the model of the 42 MW data center primary loop and secondary loop, two main components were primarily measured: pumping power and heat transfer coefficient.

Implications for Data Center Integration

Coupling nuclear energy to provide electric power and liquid-to-chip cooling loads for a 100MW data center requires a cost-aligned, solution optimized for efficient integration. In both the AP1000 and BWRX-300, similar parametric sensitivities are observed but induce different relative consequences dependent on the reactor's scale. The BWRX-300's parametric variations occur on the 100-300 MW scale, aligning naturally with the power and cooling requirements of a single hyperscale facility. The SMR's ability to operate with mechanical-draft cooling towers reduces water dependence and allows deployment in regions where an AP1000 could not be sited. Considering a grid-connected reactor, rather than an island configuration, stabilizes power delivery, reducing the impact of environmental sensitivities. Parametrically, the BWRX-300 offers more meaningful levers for performance tuning: improving reheat temperature, lowering condenser pressure, and maintaining higher steam quality directly improve cycle performance, making the SMR a more practical solution to power a single data center.

Primary Loop Analysis

In the primary loop (Table 22), the total head loss of the system was found to be 50.82 ft. The head loss is contributed by the length of the pipe, and the valving and bends of the piping system. This resulted in the system exhibiting a pumping power of 486.4 Hp. This represents the pumping horsepower required in order for the primary loop to maintain flow from the chillers throughout the system.

The primary loop system is a variable system, thus the parameters in the model can be modified. The following represents a parametric study with a variable modification of pipe diameter:

Table 22. Primary Loop Parameter Model

seg_D	seg_V	Re_{pg}	hl_{maj}
15	50.07	1.677*10^6	168.3
17	38.98	1.48*10^6	96.36
19	31.2	1.32*10^6	59.02
21	25.54	1.198*10^6	38.13
23	21.29	1.094*10^6	25.73
25	18.02	1.006*10^6	17.99
27	15.45	931770	12.96
29	13.39	867510	9.582
31	11.72	811542	7.24
33	10.34	762357	5.575
35	9.196	718794	4.365

As demonstrated, the increase in the pipe diameter in the primary loop does lead to a significant reduction in the head loss of the primary loop system. This is extremely reasonable as major head loss is inversely proportional to the pipe diameter of the system. Despite the reduction, increasing the pipe diameter does not imply a superior system.

There is a reduction in flow velocity in addition to the reduction in head loss. This is due to the flow velocity being dependent on the cross-sectional area of the pipe. Low flow velocities pose a threat to the primary loop piping system, due to corrosion and build-up implications. This can result in variable surface roughness over time within the pipe and lead to frictional losses in the system. As a result, the pump of the primary loop must be sized, optimizing the minimization of the major head loss and flow velocity of the system.

Secondary Loop Analysis

In the secondary loop of the 42 MW system, the Liebert XDU-1350 was chosen as the cooling distribution unit for liquid-to-chip applications. Utilizing the brazen plate heat exchanger of specified cooling distribution unit, the overall heat transfer coefficient was found to be 494 *Btu/(ft^2 h ^{o}F)).* The high coefficient can be attributed to the turbulent flow exhibited between the primary and secondary loops in the heat exchanger. Thus, the heat exchanger exhibits very efficient heat transfer.

Additionally, we find that the length of the brazen plate heat exchanger is 46.16 inches with 140 plates. This is well within the XDU box dimensions.

Similarly to the pumping power, the heat exchanger is a variable system in the model, thus parameters can be modified to fit the client's needs. Two parametric studies were conducted: primary loop inlet temperature (Table 23) and secondary loop outlet temperature (Table 24).

Table 23. LMTD Sensitivity to Primary Inlet Temperature

$T_{primary,cold}$	$Length_{inches}$	$LMTD$	$UA_{required}$
30	20.66	25.79	178579
32	224.1	23.78	193732
34	24.49	21.76	211727
36	27	19.73	233457
38	30.1	17.7	260242
40	34.02	15.66	294121
42	39.14	13.61	338433
44	46.16	11.54	399097
46	56.43	9.442	487853
48	73.16	7.282	632553
50	107.2	4.971	926674

Table 24. LMTD Sensitivity to Secondary Outlet Temperature

$T_{\sec ondary,cold}$	$Length_{inches}$	$LMTD$	$UA_{Required}$
45	146.3	3.641	1.265*10^6
47	86.53	6.157	748095
49	63.63	8.372	550160
51	50.76	10.5	438821
53	42.35	12.58	366186
55	36.4	14.64	314686
57	31.94	16.68	276126
59	28.47	18.72	246112
61	25.68	20.74	222055
63	23.4	22.77	202326
65	21.5	24.79	185845

Increasing the primary inlet temperature over an 18 F temperature change resulted in an increase in the length of the heat exchanger. This is understandable as an increase in the inlet temperature of the primary loop would result in a reduction in the LMTD. As previously described in the model apparatus, the UA required would increase the advent of the reduction in the LMTD, thus resulting in an increase in the area of heat exchange. The cross-sectional area of the brazen plate remains unchanged; thus, the length of the heat exchanger must increase to account for the increase in the area of heat exchange.

Inversely to the primary loop, increasing the temperature of the secondary outlet reduces the length of the heat exchanger. Assuming the inlet secondary temperature remains unchanged at 70 F, increasing the outlet temperature would result in less heat removal required in the secondary loop. As a result, the LMTD would reduce the temperature difference between the hot and cold fluids. This would reduce the UA required. As previously mentioned, the cross-sectional area of the brazen plate remains unchanged; thus, the length of the heat exchanger must decrease to account for the decrease in heat exchanged area.

Economic Analysis

LCOE Analysis

To determine the financial viability of nuclear-powered data centers, a Levelized Cost of Electricity (LCOE) analysis was conducted for both reactor types (Table 25). The LCOE represents the minimum price at which electricity must be sold to break even over the project's lifetime. The model accounts for Capital Expenditures (CAPEX), including construction, licensing, and financing; and Operating Expenditures (OPEX), covering fuel, maintenance, and staffing. Key financial assumptions include a discount rate of 7%, a plant lifespan of 60 years, and a capacity factor of 94% for the AP1000 and 90% for the BWRX-300 (conservative estimate for First-of-a-Kind SMRs). Construction costs were derived from the realized costs of Vogtle Units 3 & 4 (AP1000) and projected industry targets for the BWRX-300.

Table 25. LCOE Calculations (based on one unit of each)

2	**AP1000 Nuclear Reactor Unit (based of Vogtle Unit 3 or 4)**	**Basis**	**Units**	**Value**
	Fixed Capital Investment (CAPEX)	Total	$	$ 15,000,000,000
	Fixed Capital Investment Per Installed Unit Power (CAPEX/kW)	Cost Per Unit	$/kW	$ 13,636.36
	interest rate	Project Life	%	0.10
	Lifespan of plant (n)	Project Life	Years	60
	Capital Recovery Factor (CRF)	Project Life	-	$ 0.100329509226
	Annual Payment on Capital (CAPEX_t)	Yearly	$/yr	$ 1,504,942,638.38
	Annual Operating and Maintenance Costs (O&M)	Yearly	$/yr	$ 200,000,000
	Annual Fuel and Energy Costs	Yearly	$/yr	$ 70,000,000
	Annual Fuel and Energy Costs Per Installed Unit Power	Yearly	$/kW/yr	$ 63.64
	Total Annual Operating Expenses	Yearly	$/yr	$ 270,000,000.00
	Nameplate Capacity of the Plant (electrical output)	Initial	MW	1100
	Capacity Factor	Annual Avg	-	0.94
	Estimated Annual Generation (Gen_t)	Yearly	kWh/yr	9,057,840,000
	Levelized Cost of Electricity (LCOE)	Project Life	$/kWh	$ 0.196

1	**General Electric's BWRX-300 (One Unit)**	**Basis**	**Units**	**Value**	notes	L
	Fixed Capital Investment (CAPEX)	Total	$	$ 5,800,000,000.00		
	Fixed Capital Investment Per Installed Unit Power (CAPEX/kW)	Cost Per Unit	$/kW	$ 19,333.33		
	interest rate	Per Year	%	0.10	assume same	
	Lifespan of plant (n)	Project Life	Years	60	assume same	
	Capital Recovery Factor (CRF)	Project Life	-	0.100329509		
	Annual Payment on Capital (CAPEX_t)	Yearly	$/yr	$ 581,911,154		
	Annual Operating and Maintenance Costs (O&M)	Yearly	$/yr	$ 36,000,000	typical for SMR	
	Annual Fuel and Energy Costs	Yearly	$/yr	$ 16,556,400	matches BWR fleet fuel data	
	Annual Fuel and Energy Costs Per Installed Unit Power	Yearly	$/kW/yr	$ 55.19		
	Total Annual Operating Expenses	Yearly	$/yr	$ 52,556,400		
	Nameplate Capacity of the Plant	Initial	MW	300		
	Capacity Factor	Annual Avg	-	0.90		
	Estimated Annual Generation (Gen_t)	Yearly	kWh/yr	2,365,200,000		
	Levelized Cost of Electricity (LCOE)	Project Life	$/kWh	$ 0.268		

The analysis yielded a stark contrast in cost profiles. The AP1000 benefits from significant economies of scale. Although its total capital cost is nearly triple that of the SMR, its power output is four times greater, driving down the per-unit cost of energy. However, the absolute capital risk is immense ($15B+ per unit), creating a barrier to entry for private data center operators. The BWRX-300, while more expensive per kilowatt-hour due to "diseconomies of scale" inherent to smaller cores, offers a lower total project cost (~$5.8B). This makes financing more accessible for private entities.

Parametric Economic Analysis

Table 26. Parametric Analysis of Capacity Factor (AP1000)

Parametric Analysis of Capacity Factor (AP1000)		
Capacity Factor	**Annual Generation (kWh/yr)**	**LCOE ($/kWh)**
0.5	4818000000	$0.368
0.55	5299800000	$0.335
0.6	5781600000	$0.307
0.65	6263400000	$0.283
0.7	6745200000	$0.263
0.75	7227000000	$0.246
0.8	7708800000	$0.230
0.85	8190600000	$0.217
0.9	8672400000	$0.205
0.95	9154200000	$0.194
1	9636000000	$0.184

Table 27. Parametric Analysis of Capacity Factor (BWRX-300)

Parametric Analysis of Capacity Factor (BWRX-300)		
Capacity Factor	**Annual Generation (kWh/yr)**	**LCOE ($/kWh)**
0.5	1314000000	$0.483
0.55	1445400000	$0.439
0.6	1576800000	$0.402
0.65	1708200000	$0.371
0.7	1839600000	$0.345
0.75	1971000000	$0.322

0.8	2102400000	$0.302
0.85	2233800000	$0.284
0.9	2365200000	$0.268
0.95	2496600000	$0.254
1	2628000000	$0.241

A sensitivity analysis was performed to understand how operational reliability impacts economics (Table 26-27). Nuclear plants must run continuously to pay off their high capital costs. As the capacity factor drops from 95% to 50% (considering maintenance with frequent shutdowns or drop in generation performance), the LCOE skyrockets for both designs. For the BWRX-300, dropping to a 50% capacity factor increases the LCOE to nearly $0.50/kWh, which is economically unviable compared to grid power. This underscores that nuclear reactors must be operated as baseload sources, as they cannot economically throttle to match fluctuating data center loads. The data center load must remain flat, or the reactor must have a secondary off taker (the grid) for its surplus power.

Situational Analysis

The economic comparison between the BWRX-300 and the AP1000 extends beyond simple unit costs to encompass scalability, deployment risk, and the maturity of the technology. While the BWRX-300 offers a lower absolute entry price suitable for smaller, isolated facilities, the AP1000 demonstrates superior cost-effectiveness when scaling to support the massive infrastructure requirements of modern cloud computing giants. A single AP1000 unit produces approximately 1,100 to 1,200 MWe. While this creates an oversizing issue for a single data center, it becomes a distinct advantage for hyperscale campuses. Tech giants like Google and Amazon are increasingly developing mega campuses with multiple data center halls. In this context, the AP1000 serves as a centralized power hub, offering a significantly lower investment cost per kilowatt of generated output compared to chaining together multiple, more expensive SMR units.

Furthermore, the theoretical economic advantages of the BWRX-300 rely heavily on unproven assumptions regarding modularity and learning curves. The nuclear industry has a history of underestimating the "First-of-a-Kind" premiums associated with new reactor designs. There is a substantial risk that the BWRX-300 has overpromised pricing and deployment speed, particularly regarding the licensing of its novel safety systems and the establishment of a supply chain for modular components. In contrast, the AP1000 is a mature, licensed technology. Following the completion of Vogtle Units 3 and 4, the supply chain and workforce are established, drastically reducing the risk profile for subsequent units. Recent industry projections for powering Google Cloud data centers suggest a fleet deployment cost of approximately $80 billion for ten AP1000 reactors, averaging just $8 billion per unit. This dramatic reduction from historical costs fundamentally shifts the value proposition in favor of the large PWR for fleet-scale operations.

Overall Economics

To understand the true scale of investment required for these nuclear-integrated facilities, an overall economic assessment was performed. This analysis combines the capital costs of the nuclear generation with the construction costs of the data center clusters they support. The baseline assumption remains a standard data center annual consumption of 1.05 TWh and a facility construction cost of approximately $2.41 billion per data center based on the Ashburn, Virginia Data Center costs.

AP1000 Hypergrid Scenerio

Because of its massive output, a single AP1000 reactor can support approximately nine distinct data centers. The total annual energy value generated for this cluster is calculated by multiplying the annual consumption per center by the LCOE and the number of supported facilities:

Annual Cost = 1,051,200,000 kWh×$0.196/kWh×9 Data Centers ≈ **$1.85 Billion**

The total capital investment required to build this massive ecosystem includes the $15 billion reactor and nine data centers:

Net Investment = $15,000,000,000+($2,413,859,194×9) ≈ **$36.7 Billion**

BWRX-300 Modular Cluster Scenerio

The SMR scenario is sized for a smaller cluster, where one BWRX-300 supports two data centers. The annual energy cost for this configuration is:

Annual Cost = 1,051,200,000 kWh×$0.268/kWh×2 Data Centers ≈ **$563** Million

The total capital investment for this modular cluster is much lower, reducing the barrier to entry:

Net Investment = $\$5,800,000,000+(\$2,413,859,194\times2) \approx$ **$10.6** Billion

Comparison and Scalability

The economic evaluation presents a clear dichotomy between high-efficiency centralized infrastructure and flexible modular deployment. The AP1000 offers superior long-term value through economies of scale, achieving a significantly lower LCOE of $0.196/kWh. However, this efficiency requires an immense upfront capital commitment of approximately $36.7 billion. This magnitude of investment creates an exceptionally high barrier to entry, effectively limiting this solution to the largest hyperscale technology companies or state-backed utility partnerships capable of financing a gigawatt-scale ecosystem.

In contrast, the BWRX-300 scenario functions as an easier model for entry. While the energy cost is higher at $0.268/kWh, the total project capitalization of $10.6 billion represents a roughly 70% reduction in initial financial exposure compared to the AP1000 hypergrid. This lower capital requirement allows operators to align infrastructure spending more closely with demand as a company can bring 300 MW of capacity online to support two data centers without committing to the infrastructure required for nine. Therefore, while the AP1000 yields the highest return on investment for fully developed mega-campuses, the BWRX-300 provides a necessary pathway for phased growth, reducing the risk of stranded capital and allowing for deployment in markets that cannot support a 1.2 GW baseload.

Conclusion

Summary of Findings

This project successfully modeled and compared the integration of AP1000 and BWRX-300 nuclear reactors with a 100 MW liquid cooled data center, revealing a fundamental dichotomy between economic efficiency and operational feasibility. The thermodynamic and economic analyses demonstrate that the AP1000 is the winner in terms of raw efficiency, achieving a Levelized Cost of Electricity (LCOE) of $0.196/kWh due to its massive economies of scale. However, its 1,224 MW net output is structurally incompatible with a dedicated, single facility application. Furthermore, the requirement for nearly 50,000 kg/s of cooling water geographically tethers the AP1000 to major water bodies, limiting deployment flexibility. In contrast, the BWRX-300 SMR, despite a higher LCOE of $0.268/kWh, emerges as the superior strategic choice for behind-the-meter deployment. Its 300 MW capacity offers an ideal fit, powering the 100 MW IT load and 20 MW cooling load while retaining a healthy buffer for future AI cluster expansion, without the massive $37 billion capital exposure required for the AP1000 "Hypergrid" scenario. While natural gas in current standards is significantly less expensive to the customer in terms of LCOE, nuclear energy provides a more viable long-term option as it is heavily skewed by initial investment costs which depreciate over time and also allows for 24/7 runtime of carbon-free energy which is preferable for data centers.

Operational Sensitivities and Thermodynamics

The parametric studies highlighted that while nuclear power provides baseload reliability, it is not immune to environmental constraints. Both reactor designs exhibited a thermal efficiency penalty of approximately 9% when ambient temperatures rose from 5°C to 35°C, resulting in a loss of over 100 MW of capacity for the AP1000 during peak summer conditions. This underscores the necessity of oversizing the cooling infrastructure to maintain the chilled water loop temperatures required by high density AI chips. Exergy analysis further identified that the majority of thermodynamic losses occur in the reactor core and steam generator, suggesting that while the Rankine cycle is mature, the integration efficiency is ultimately limited by the heat rejection temperature. The SMR's ability to utilize mechanical draft cooling towers and its lower absolute water footprint (approx. 15,000 kg/s) provides a decisive advantage for data centers seeking to locate near fiber optic hubs in water scarce regions.

Limitations

This study was primarily limited by the assumption of steady state thermodynamic operation, which does not account for the transient reactor physics required to match the rapid sub-second load fluctuations typical of AI training workloads. Both reactor types face significant challenges in load following capabilities; while SMRs are theoretically more agile, large PWRs like the AP1000 have the thermal inertia to ride through minor grid disturbances more effectively. Furthermore, the economic advantage of the BWRX-300 relies heavily on unproven cost projections and a supply chain that does not yet exist. In contrast, the AP1000 represents a mature, licensed technology with known costs, making it a lower risk option for massive, gigawatt scale energy needs where multiple data centers are co-located. While the power draw of the data center system was assumed to intake 100 MW, it is imperative to acknowledge all data centers reflect different power draws. This is contributed by the use of different equipment manufacturers, varied cooling loads, varied IT loads, and more. Due to the lack of public data regarding equipment within data center facilities, the personalized data center design solely focuses on the cooling loop.

Further Studies

Future research must prioritize dynamic modeling to assess how both reactor designs handle sudden trips in GPU power draw without triggering safety scrams. Additionally, to improve the economic viability of nuclear integration regardless of reactor size, further studies should investigate energy ecosystem concepts, such as utilizing condenser waste heat for district heating or diverting excess generation capacity to high temperature steam electrolysis for hydrogen production. Finally, as the industry moves toward grid independence, further analysis is required to compare these fission-based solutions against emerging technologies like fusion energy or hybrid microgrids that integrate nuclear baseload with battery energy storage systems to ensure true 24/7 reliability in an islanded mode.

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{ME 4315: Energy Systems Analysis and Design Project Model for Westinghouse AP1000}
$UnitSystem SI C kPa kJ

{GIVEN INFORMATION & ASSUMPTIONS}

{Primary Loop Data from PDF pg. 27}
P_primary_op = 15.5 [MPa] * Convert(MPa, kPa)
T_P1_given = 321.1 [C]
T_P2_given = 280.7 [C]
V_dot_primary_per_loop = 9.94 [m^3/s]
N_loops = 2
eta_p_primary = 0.85

{Secondary Loop Data from PDF pg. 27 & 29}
P_S1 = 5.76 [MPa] * Convert(MPa, kPa)
x_S1 = 1
P_cond = 9.1 [kPa]
m_dot_secondary_plant = 1886 [kg/s]

{Modeling Assumptions for Secondary Loop}
P_crossover = 1000 [kPa]
eta_t_LP = 0.88
eta_t_HP = eta_t_LP
eta_p_secondary = 0.85

{PRIMARY LOOP ANALYSIS (LOOP 1)}

P_P1 = P_primary_op
h_P1 = Enthalpy(Water, P=P_P1, T=T_P1_given)
s_P1 = Entropy(Water, P=P_P1, T=T_P1_given)

P_P2 = P_primary_op
h_P2 = Enthalpy(Water, P=P_P2, T=T_P2_given)
s_P2 = Entropy(Water, P=P_P2, T=T_P2_given)
v_P2 = Volume(Water, P=P_P2, T=T_P2_given)

V_dot_primary_total = V_dot_primary_per_loop * N_loops
m_dot_primary = V_dot_primary_total / v_P2

deltaP_primary_loop = 0.5 [MPa] * Convert(MPa, kPa)
w_p_primary_s = v_P2 * deltaP_primary_loop
w_p_primary = w_p_primary_s / eta_p_primary
h_P3 = h_P2 + w_p_primary
T_P3 = Temperature(Water, P=P_primary_op + deltaP_primary_loop, h=h_P3)

W_dot_p_primary = (m_dot_primary * w_p_primary) / 1000
Q_dot_reactor = (m_dot_primary * (h_P1 - h_P3)) / 1000
Q_dot_SG = (m_dot_primary * (h_P1 - h_P2)) / 1000

{State S1: HP Turbine Inlet}
h_S1 = Enthalpy(Water, P=P_S1, x=x_S1)
s_S1 = Entropy(Water, P=P_S1, x=x_S1)
T_S1 = Temperature(Water, P=P_S1, x=x_S1)
s_S2s = s_S1
h_S2s = Enthalpy(Water, P=P_crossover, s=s_S2s)
P_S2 = P_crossover
eta_t_HP = (h_S1 - h_S2) / (h_S1 - h_S2s)
T_S2 = Temperature(Water, P=P_crossover, h=h_S2)
P_S3 = P_crossover
x_S3 = 1
h_S3 = Enthalpy(Water, P=P_S3, x=x_S3)
s_S3 = Entropy(Water, P=P_S3, x=x_S3)
```

```
s_S4s = s_S3  {Isentropic expansion}
h_S4s = Enthalpy(Water, P=P_cond, s=s_S4s)  {Ideal Enthalpy}
h_S4 = h_S3 - eta_t_LP * (h_S3 - h_S4s)
P_S4 = P_cond
x_S4 = Quality(Water, P=P_cond, h=h_S4)
s_S4 = Entropy(Water, P=P_cond, h=h_S4)
T_S4 = Temperature(Water, P=P_cond, h=h_S4)
P_S5 = P_cond
x_S5 = 0
h_S5 = Enthalpy(Water, P=P_S5, x=x_S5)
s_S5 = Entropy(Water, P=P_S5, x=x_S5)
v_S5 = Volume(Water, P=P_S5, x=x_S5)
T_S5 = Temperature(Water, P=P_S5, x=x_S5)
P_S6 = P_crossover
w_p_cond_s = v_S5 * (P_S6 - P_S5)
w_p_cond = w_p_cond_s / eta_p_secondary
h_S6 = h_S5 + w_p_cond
T_S6 = Temperature(Water, P=P_S6, h=h_S6)
y * h_S2 + (1 - y) * h_S6 = 1 * h_S7
P_S7 = P_crossover
x_S7 = 0
h_S7 = Enthalpy(Water, P=P_S7, x=x_S7)
s_S7 = Entropy(Water, P=P_S7, x=x_S7)
v_S7 = Volume(Water, P=P_S7, x=x_S7)
T_S7 = Temperature(Water, P=P_S7, x=x_S7)
P_S8 = P_S1
w_p_feed_s = v_S7 * (P_S8 - P_S7)
w_p_feed = w_p_feed_s / eta_p_secondary
h_S8 = h_S7 + w_p_feed
T_S8 = Temperature(Water, P=P_S8, h=h_S8)
Q_dot_out_model = (m_dot_secondary * (1-y) * (h_S4 - h_S5)) / 1000
s_S2 = Entropy(Water, P=P_crossover, h=h_S2)
s_S6 = Entropy(Water, P=P_crossover, h=h_S6)
s_S8 = Entropy(Water, P=P_S1, h=h_S8)

{TERTIARY LOOP (HEAT REJECTION) ANALYSIS (LOOP 3)}
T_cooling_in_C = 30.5 [C]
delta_T_cooling_C = 12 [C]
T_cooling_out_C = T_cooling_in_C + delta_T_cooling_C
T_cooling_avg_C = (T_cooling_in_C + T_cooling_out_C) / 2
c_p_cooling = Cp(Water, T=T_cooling_avg_C, P=101.3[kPa])
Q_dot_out_model * 1000 = m_dot_cooling * c_p_cooling * delta_T_cooling_C
v_cooling = Volume(Water, T=T_cooling_avg_C, P=101.3[kPa])
V_dot_cooling = m_dot_cooling * v_cooling

{SYSTEM-WIDE POWER & EFFICIENCY}
W_dot_t_HP = (m_dot_secondary * (h_S1 - h_S2)) / 1000
W_dot_t_LP = ((1 - y) * m_dot_secondary * (h_S3 - h_S4)) / 1000
W_dot_t_total = W_dot_t_HP + W_dot_t_LP
W_dot_p_cond = ((1 - y) * m_dot_secondary * w_p_cond) / 1000
W_dot_p_feed = (m_dot_secondary * w_p_feed) / 1000
W_dot_p_secondary_total = W_dot_p_cond + W_dot_p_feed
W_dot_net_secondary = W_dot_t_total - W_dot_p_secondary_total
W_dot_net_model = W_dot_net_secondary - W_dot_p_primary
eta_th_overall = W_dot_net_model / Q_dot_reactor
eta_th_overall_percent = eta_th_overall * 100

{ EXERGY ANALYSIS }

Q_dot_SG * 1000 = m_dot_secondary * (h_S1 - h_S8)
```

```
{DEAD STATE DEFINITION}
T0_C = 25 [C]              {Dead state temp in Celsius}
T0_K = T0_C + 273.15
P0 = 101.3 [kPa]
h0 = Enthalpy(Water, T=T0_C, x=0)
s0 = Entropy(Water, T=T0_C, x=0)

{SPECIFIC FLOW EXERGY (kJ/kg)}

ex_P1 = (h_P1 - h0) - T0_K*(s_P1 - s0)
ex_P2 = (h_P2 - h0) - T0_K*(s_P2 - s0)

ex_S1 = (h_S1 - h0) - T0_K*(s_S1 - s0)
ex_S2 = (h_S2 - h0) - T0_K*(s_S2 - s0)
ex_S3 = (h_S3 - h0) - T0_K*(s_S3 - s0)
ex_S4 = (h_S4 - h0) - T0_K*(s_S4 - s0)
ex_S5 = (h_S5 - h0) - T0_K*(s_S5 - s0)
ex_S6 = (h_S6 - h0) - T0_K*(s_S6 - s0)
ex_S7 = (h_S7 - h0) - T0_K*(s_S7 - s0)
ex_S8 = (h_S8 - h0) - T0_K*(s_S8 - s0)

{TOTAL EXERGY RATES [MW]}

Ex_dot_P1 = (m_dot_primary * ex_P1) / 1000
Ex_dot_P2 = (m_dot_primary * ex_P2) / 1000

Ex_dot_S1 = (m_dot_secondary * ex_S1) / 1000
Ex_dot_S2 = (m_dot_secondary * ex_S2) / 1000
Ex_dot_S3 = (m_dot_secondary * (1-y) * ex_S3) / 1000
Ex_dot_S4 = (m_dot_secondary * (1-y) * ex_S4) / 1000
Ex_dot_S5 = (m_dot_secondary * (1-y) * ex_S5) / 1000
Ex_dot_S6 = (m_dot_secondary * (1-y) * ex_S6) / 1000
Ex_dot_S7 = (m_dot_secondary * ex_S7) / 1000
Ex_dot_S8 = (m_dot_secondary * ex_S8) / 1000

{EXERGY INPUT (From Nuclear Fuel)}
T_fuel_K = 3000 [K] {Effective fuel temperature}
Ex_in_total = Q_dot_reactor * (1 - T0_K/T_fuel_K) {[MW]}

{EXERGY DESTRUCTION CALCULATIONS [MW]}

{Reactor Core}
Ex_dest_reactor = Ex_in_total - (Ex_dot_P1 - Ex_dot_P2)

{Steam Generator (SG)}
Ex_dest_SG = (Ex_dot_P1 - Ex_dot_P2) - (Ex_dot_S1 - Ex_dot_S8)

{Turbines}
Ex_dest_HP = (Ex_dot_S1 - Ex_dot_S2) - W_dot_t_HP
Ex_dest_LP = (Ex_dot_S3 - Ex_dot_S4) - W_dot_t_LP

{Pumps}
Ex_dest_cond_pump = (Ex_dot_S5 - Ex_dot_S6) + W_dot_p_cond
Ex_dest_feed_pump = (Ex_dot_S7 - Ex_dot_S8) + W_dot_p_feed

{Feedwater Heater (OFWH)}
Ex_bleed_in = (m_dot_secondary * y * ex_S2) / 1000
Ex_dest_FWH = (Ex_bleed_in + Ex_dot_S6) - Ex_dot_S7

{Condenser (Loss to Environment)}
{Dynamic cooling water calculation}
```

```
T_cond_avg_K = (T_cooling_in_C + T_cooling_out_C)/2 + 273.15
Ex_loss_env = Q_dot_out_model * (1 - T0_K/T_cond_avg_K)
Ex_dest_cond = (Ex_dot_S4 - Ex_dot_S5) - Ex_loss_env

{BALANCE CHECK}
Ex_total_losses = Ex_dest_reactor + Ex_dest_SG + Ex_dest_HP + Ex_dest_LP + Ex_dest_cond_pump +
Ex_dest_feed_pump +Ex_dest_FWH + Ex_dest_cond + Ex_loss_env

eta_exergy = W_dot_net_model / Ex_in_total
eta_exergy_pct = 100 * eta_exergy

Ex_balance = Ex_in_total - (W_dot_net_model + Ex_total_losses)

{TERTIARY LOOP (Physical Water Req)}
Q_condenser_kW = Q_dot_out_model * 1000 {Conversion for property calls}

cp_cw = Cp(Water, T=T_cooling_avg_C, P=P0) {kJ/kg-K}
v_cw = Volume(Water, T=T_cooling_avg_C, P=P0) {m^3/kg}

m_dot_cw = Q_condenser_kW / (cp_cw * delta_T_cooling_C) {kg/s}
V_dot_cw = m_dot_cw * v_cw {m^3/s}


{Pressure Array}
P[1] = P_S1    {HP Turbine Inlet}
P[2] = P_S2    {HP Turbine Outlet}
P[3] = P_S3    {LP Turbine Inlet}
P[4] = P_S4    {LP Turbine Outlet}
P[5] = P_S5    {Condenser Outlet}
P[6] = P_S6    {Condensate Pump Outlet}
P[7] = P_S7    {FWH Outlet}
P[8] = P_S8    {Steam Generator Inlet}

{Temperature Array}
T[1] = T_S1
T[2] = T_S2
T[3] = T_S3
T[4] = T_S4
T[5] = T_S5
T[6] = T_S6
T[7] = T_S7
T[8] = T_S8

{Enthalpy Array}
h[1] = h_S1
h[2] = h_S2
h[3] = h_S3
h[4] = h_S4
h[5] = h_S5
h[6] = h_S6
h[7] = h_S7
h[8] = h_S8

{Entropy Array}
s[1] = s_S1
s[2] = s_S2
s[3] = s_S3
s[4] = s_S4
s[5] = s_S5
s[6] = s_S6
s[7] = s_S7
```

s[8] = s_S8

{ Quality Array}

x[1] = x_S1
x[2] = **Quality**(***Water***, ***P***=P_S2, ***h***=h_S2) {Calculate quality at HP exit}
x[3] = x_S3
x[4] = x_S4
x[5] = 0 {Liquid}
x[6] = 0 {Liquid}
x[7] = 0 {Liquid}
x[8] = 0 {Liquid}

{Exergy Array}
ex[1] = ex_S1
ex[2] = ex_S2
ex[3] = ex_S3
ex[4] = ex_S4
ex[5] = ex_S5
ex[6] = ex_S6
ex[7] = ex_S7
ex[8] = ex_S8

SOLUTION

Unit Settings: SI C kPa kJ mass deg

cp_{cw} = 4.179 [kJ/kg-K]	$c_{p,cooling}$ = 4.179 [kJ/kg-K]
$\delta P_{primary,loop}$ = 500 [kPa]	$\delta_{T,cooling,C}$ = 12 [C]
η_{exergy} = 0.4024	$\eta_{exergy,pct}$ = 40.24 [%]
$\eta_{p,primary}$ = 0.85	$\eta_{p,secondary}$ = 0.85
$\eta_{th,overall}$ = 0.3624	$\eta_{th,overall,percent}$ = 36.24 [%]
$\eta_{t,HP}$ = 0.88	$\eta_{t,LP}$ = 0.88
$Ex_{balance}$ = -104 [MW]	$Ex_{bleed,in}$ = 303.2 [MW]
$Ex_{dest,cond}$ = 56.56 [MW]	$Ex_{dest,cond,pump}$ = 0.2097 [MW]
$Ex_{dest,feed,pump}$ = 1.053 [MW]	$Ex_{dest,FWH}$ = 89.69 [MW]
$Ex_{dest,HP}$ = 41.93 [MW]	$Ex_{dest,LP}$ = 100.1 [MW]
$Ex_{dest,reactor}$ = 1412 [MW]	$Ex_{dest,SG}$ = 128.1 [MW]
$\dot{E}x_{P1}$ = 6681 [MW]	$\dot{E}x_{P2}$ = 5050 [MW]
$\dot{E}x_{S1}$ = 1730 [MW]	$\dot{E}x_{S2}$ = 1221 [MW]
$\dot{E}x_{S3}$ = 1033 [MW]	$\dot{E}x_{S4}$ = 152.2 [MW]
$\dot{E}x_{S5}$ = 3.064 [MW]	$\dot{E}x_{S6}$ = 4.34 [MW]
$\dot{E}x_{S7}$ = 217.8 [MW]	$\dot{E}x_{S8}$ = 227.4 [MW]
$Ex_{in,total}$ = 3042 [MW]	$Ex_{loss,env}$ = 92.56 [MW]
ex_{P1} = 440.4 [kJ/kg]	ex_{P2} = 332.9 [kJ/kg]
ex_{S1} = 1030 [kJ/kg]	ex_{S2} = 726.8 [kJ/kg]
ex_{S3} = 818.4 [kJ/kg]	ex_{S4} = 120.6 [kJ/kg]
ex_{S5} = 2.427 [kJ/kg]	ex_{S6} = 3.438 [kJ/kg]
ex_{S7} = 129.7 [kJ/kg]	ex_{S8} = 135.4 [kJ/kg]
$Ex_{total,losses}$ = 1922	h0 = 104.8 [kJ/kg]
h_{P1} = 1460 [kJ/kg]	h_{P2} = 1236 [kJ/kg]
h_{P3} = 1237 [kJ/kg]	h_{S1} = 2787 [kJ/kg]
h_{S2} = 2509 [kJ/kg]	h_{S2s} = 2471 [kJ/kg]
h_{S3} = 2777 [kJ/kg]	h_{S4} = 2159 [kJ/kg]
h_{S4s} = 2074 [kJ/kg]	h_{S5} = 184.1 [kJ/kg]
h_{S6} = 185.3 [kJ/kg]	h_{S7} = 762.5 [kJ/kg]
h_{S8} = 768.8 [kJ/kg]	$\dot{m}_{cooling}$ = 49696 [kg/s]

$\dot{m}_{secondary}$ = 1680 [kg/s]
N_{loops} = 2
P_{cond} = 9.1 [kPa]
P_{P1} = 15500 [kPa]
$P_{primary,op}$ = 15500 [kPa]
P_{S2} = 1000
P_{S4} = 9.1
P_{S6} = 1000 [kPa]
P_{S8} = 5760 [kPa]
$\dot{Q}_{out,model}$ = 2492 [MW]
$\dot{Q}_{SG}$ = 3390 [MW]
s_{P1} = 3.435 [kJ/kg-K]
s_{S1} = 5.909 [kJ/kg-K]
s_{S2s} = 5.909 [kJ/kg-K]
s_{S4} = 6.851 [kJ/kg-K]
s_{S5} = 0.6251 [kJ/kg-K]
s_{S7} = 2.138 [kJ/kg-K]
$T0_C$ = 25 [C]
$T_{cond,avg,K}$ = 309.7 [K]
$T_{cooling,in,C}$ = 30.5 [C]
$T_{fuel,K}$ = 3000 [K]
$T_{P2,given}$ = 280.7 [C]
T_{S1} = 272.9 [C]
T_{S3} = 179.9 [C]
T_{S5} = 43.97
T_{S7} = 179.9
$v_{cooling}$ = 0.001007 [m^3/kg]
$\dot{V}_{cooling}$ = 50.02 [m^3/s]
$\dot{V}_{primary,per,loop}$ = 9.94 [m^3/s]
v_{P2} = 0.00131 [m^3/kg]
v_{S7} = 0.001127 [m^3/kg]
$\dot{W}_{net,secondary}$ = 1236 [MW]
$\dot{W}_{p,feed}$ = 10.6 [MW]
$\dot{W}_{p,secondary,total}$ = 12.09 [MW]
$\dot{W}_{t,LP}$ = 780.9 [MW]
$w_{p,cond}$ = 1.177
$w_{p,feed}$ = 6.312
$w_{p,primary}$ = 0.7709
x_{S1} = 1
x_{S4} = 0.8239
x_{S7} = 0

$\dot{m}_{secondary,plant}$ = 1886 [kg/s]
P0 = 101.3 [kPa]
$P_{crossover}$ = 1000 [kPa]
P_{P2} = 15500 [kPa]
P_{S1} = 5760 [kPa]
P_{S3} = 1000 [kPa]
P_{S5} = 9.1 [kPa]
P_{S7} = 1000 [kPa]
$Q_{condenser,kW}$ = 2.492E+06 [kW]
$\dot{Q}_{reactor}$ = 3378 [MW]
s0 = 0.3672 [kJ/kg-K]
s_{P2} = 3.046 [kJ/kg-K]
s_{S2} = 5.993 [kJ/kg-K]
s_{S3} = 6.585 [kJ/kg-K]
s_{S4s} = 6.585 [kJ/kg-K]
s_{S6} = 0.6257 [kJ/kg-K]
s_{S8} = 2.14 [kJ/kg-K]
$T0_K$ = 298.2 [K]
$T_{cooling,avg,C}$ = 36.5 [C]
$T_{cooling,out,C}$ = 42.5 [C]
$T_{P1,given}$ = 321.1 [C]
T_{P3} = 280.9 [C]
T_{S2} = 179.9 [C]
T_{S4} = 43.97 [C]
T_{S6} = 44.05
T_{S8} = 180.8 [C]
v_{cw} = 0.001007 [m^3/s]
$\dot{V}_{cw}$ = 50.02 [m^3/s]
$\dot{V}_{primary,total}$ = 19.88 [m^3/s]
v_{S5} = 0.001009 [m^3/kg]
$\dot{W}_{net,model}$ = 1224 [MW]
$\dot{W}_{p,cond}$ = 1.486 [MW]
$\dot{W}_{p,primary}$ = 11.69 [MW]
$\dot{W}_{t,HP}$ = 467.2 [MW]
$\dot{W}_{t,total}$ = 1248 [MW]
$w_{p,cond,s}$ = 1
$w_{p,feed,s}$ = 5.366
$w_{p,primary,s}$ = 0.6552
x_{S3} = 1
x_{S5} = 0
y = 0.2484

No unit problems were detected.

Arrays Table: Main

	s_i	T_i	x_i	ex_i	h_i	P_i
1	5.909	272.9	1	1030	2787	5760
2	5.993	179.9	0.8669	726.8	2509	1000
3	6.585	179.9	1	818.4	2777	1000
4	6.851	43.97	0.8239	120.6	2159	9.1
5	0.6251	43.97	0	2.427	184.1	9.1
6	0.6257	44.05	0	3.438	185.3	1000
7	2.138	179.9	0	129.7	762.5	1000
8	2.14	180.8	0	135.4	768.8	5760

Parametric Table: Table 1

	P_{cond} [kPa]	$\dot{W}_{net,model}$ [MW]	$\eta_{th,overall}$	x_{S4}	$Ex_{total,losses}$	$\eta_{exergy,pct}$ [%]
Run 1	5	1282	0.3795	0.8097	1862	42.14
Run 2	6	1265	0.3745	0.8139	1880	41.58
Run 3	7	1250	0.3701	0.8175	1895	41.09
Run 4	8	1237	0.3662	0.8207	1909	40.66
Run 5	9	1225	0.3628	0.8236	1921	40.28
Run 6	10	1215	0.3596	0.8262	1932	39.93
Run 7	11	1205	0.3567	0.8286	1942	39.6
Run 8	12	1196	0.354	0.8308	1952	39.31
Run 9	13	1187	0.3515	0.8328	1961	39.03
Run 10	14	1179	0.3491	0.8347	1969	38.77
Run 11	15	1172	0.3469	0.8365	1977	38.52

Parametric Table: Table 2

	$P_{crossover}$ [kPa]	$\eta_{th,overall}$	y	$\dot{W}_{net,model}$ [MW]	$Ex_{total,losses}$	$\eta_{exergy,pct}$ [%]
Run 1	500	0.3657	0.2044	1235	1922	40.61
Run 2	650	0.3652	0.2206	1234	1921	40.55
Run 3	800	0.3642	0.2338	1230	1921	40.44
Run 4	950	0.3629	0.245	1226	1922	40.29
Run 5	1100	0.3614	0.2548	1221	1923	40.13
Run 6	1250	0.3599	0.2636	1216	1924	39.96
Run 7	1400	0.3583	0.2715	1210	1926	39.78
Run 8	1550	0.3566	0.2787	1205	1928	39.6
Run 9	1700	0.355	0.2854	1199	1930	39.41
Run 10	1850	0.3533	0.2916	1193	1932	39.22
Run 11	2000	0.3515	0.2975	1188	1934	39.03

Parametric Table: Table 3

	$\eta_{t,HP}$	$\eta_{th,overall}$	$\dot{W}_{net,model}$ [MW]	$\dot{Q}_{out,model}$ [MW]	$\eta_{exergy,pct}$ [%]	$Ex_{total,losses}$
Run 1	0.9	0.3654	1234	2490	40.57	1915
Run 2	0.86	0.3595	1214	2495	39.92	1929
Run 3	0.82	0.3536	1195	2499	39.26	1944
Run 4	0.78	0.3477	1175	2503	38.61	1959
Run 5	0.74	0.3418	1155	2508	37.96	1973
Run 6	0.7	0.336	1135	2512	37.3	1988
Run 7	0.66	0.3301	1115	2516	36.65	2002
Run 8	0.62	0.3242	1095	2520	35.99	2017
Run 9	0.58	0.3183	1075	2525	35.34	2031
Run 10	0.54	0.3124	1055	2529	34.68	2046
Run 11	0.5	0.3064	1035	2533	34.03	2060

Parametric Table: Table 4

	$T0_C$	$Ex_{in,total}$	$Ex_{loss,env}$	$Ex_{total,losses}$	$\eta_{exergy,pct}$
	[C]	[MW]	[MW]		[%]
Run 1	5	3065	253.5	1960	39.95
Run 2	9.5	3060	217.3	1951	40.01
Run 3	14	3055	181.1	1943	40.08
Run 4	18.5	3050	144.9	1934	40.15
Run 5	23	3045	108.7	1926	40.21
Run 6	27.5	3040	72.44	1917	40.28
Run 7	32	3035	36.22	1909	40.35
Run 8	36.5	3029	0	1901	40.41
Run 9	41	3024	-36.22	1892	40.48
Run 10	45.5	3019	-72.44	1884	40.55
Run 11	50	3014	-108.7	1875	40.62

```
$UnitSystem ENG F psia mass deg


"Chiller Data"
Chiller_n = 24 "Number of chillers without redundancy"
chiller_operating_f = 1149 "Operating flow rate of York YVAA in GPM"

Total_flow_rate_GPM = chiller_operating_f * Chiller_n "Total flow rate in GPM"
Total_flow_cfs = Total_flow_rate_GPM * 0.002228 "Conversion to cubic feet per second"

"Primary Loop Layout"
N_seg = 25 "Number of segmentation valves"
n_b = 4 "Number of bends"
seg_D = 24 "Valve/Pipe diameter in inches"
seg_D_ft = seg_D / 12 "Diameter in feet"
Total_l = (4 * seg_D_ft * 25 * 2) + (80 * 2) "Total length of primary loop"

"30% Propylene Glycol at approx 50 F"
rho_pg = 64.32 "Density [lb/ft^3] - User value"
mu_pg = 0.0024 "Dynamic Viscosity [lbm/ft-s] (Corrected for 30% PG)"
cp_primary = 0.93 "Specific Heat [Btu/lb-F] - User value"
k_pg = 0.25 "Thermal Conductivity [Btu/hr-ft-F] (Typical for 30% PG)"
Pr_pg = 25 "Prandtl Number (Typical for 30% PG)"

A_pipe = pi * (seg_D_ft/2)^2 "Cross sectional area"
seg_V = Total_flow_cfs / A_pipe "Flow velocity [ft/s]"

"Reynolds Number Calculation"
Re_pg = (rho_pg * seg_V * seg_D_ft) / mu_pg

"Friction Factor (Haaland Equation)"
e = 0.00015 "Surface roughness for steel pipe [ft]"
"Implicit solve for f:"
f = ( -1.8 * Log10( ( (e/seg_D_ft)/3.7 )^1.11 + 6.9/Re_pg ) )^(-2)

"Major Loss Head Loss Calcs"
g = 32.2
hl_maj = f * (Total_l / seg_D_ft) * (seg_V^2 / (2*g)) "Major Head Loss [ft]"

"Minor Loss Head Loss Calcs"
"Assuming K values based on user original logic"
K_valve = 0.15
K_bend = 0.3
K_total = (N_seg * K_valve) + (n_b * K_bend)
hl_min = K_total * (seg_V^2 / (2*g)) "Minor Head Loss [ft]"

Total_Head_Loss = hl_maj + hl_min

"Pump Sizing"
eta_pump = 0.75 "Pump efficiency"
"Power = (Flow_GPM * Head_ft * SG) / (3960 * eff)"
SG_pg = rho_pg / 62.4
p_hp = (Total_flow_rate_GPM * Total_Head_Loss * SG_pg) / (3960 * eta_pump) "Pump Horsepower"


" HEAT TRANSFER PROBLEM"

"Givens"
Q_dot_kW = 1350 "Rating from XDU-1350 manual [kW]"
Q_dot_Btu = Q_dot_kW * 3412 "Convert to Btu/hr"

T_primary_cold = 44 "Chiller Supply Temp [F]"
T_primary_hot = T_primary_cold + 10 "Chiller Return Temp [F]"
```

```
T_secondary_cold = 52 "Server Supply Temp [F]"
T_secondary_hot = T_secondary_cold + 18 "Server Return Temp [F]"

cp_secondary = 0.935 "Specific heat capacity"

" Mass Flow Calculations"
m_dot_primary = Q_dot_Btu / (cp_primary * (T_primary_hot - T_primary_cold))
m_dot_secondary = Q_dot_Btu / (cp_secondary * (T_secondary_hot - T_secondary_cold))

" LMTD Calculation (Counter-Flow"
dT1 = T_secondary_hot - T_primary_hot  "Hot In - Cold Out"
dT2 = T_secondary_cold - T_primary_cold "Hot Out - Cold In"
LMTD = (dT1 - dT2) / Ln(dT1/dT2)

"Required UA"
UA_required = Q_dot_Btu / LMTD "[Btu/hr-F]"


" FINDING LENGTH (BRAZED PLATE METHOD)"

"Assumed Geometry for XDU-1350"
N_plates = 140 "Estimated number of plates"
Plate_Width = 1.5 "Width in feet"
Plate_Gap = 0.008 "Gap in feet (approx 2.4mm)"
D_hydraulic = 2 * Plate_Gap "Hydraulic diameter"

"We assume flow is split evenly between plates"
Flow_Area = (N_plates / 2) * Plate_Width * Plate_Gap

G_pri = m_dot_primary / Flow_Area / 3600
G_sec = m_dot_secondary / Flow_Area / 3600

"Reynolds Numbers inside the Plate"
Re_plate_pri = (G_pri * D_hydraulic) / mu_pg
Re_plate_sec = (G_sec * D_hydraulic) / mu_pg

"Nusselt Correlations for Chevron Plates (Nu = 0.2 * Re^0.67 * Pr^0.4)"
Nu_pri = 0.2 * Re_plate_pri^0.67 * Pr_pg^0.4
Nu_sec = 0.2 * Re_plate_sec^0.67 * Pr_pg^0.4

h_pri = (Nu_pri * k_pg) / D_hydraulic
h_sec = (Nu_sec * k_pg) / D_hydraulic

U_overall = 1 / ( (1/h_pri) + (1/h_sec) )


Total_Area = UA_required / U_overall
Length_ft = Total_Area / (N_plates * Plate_Width) "Calculated Length in Feet"
Length_in = Length_ft * 12 "Calculated Length in Inches"
```

SOLUTION

Unit Settings: Eng F psia mass deg

A_{pipe} = 3.142 [ft^2]	$Chiller_n$ = 24	$chiller_{operating,f}$ = 1149 [gpm]
$cp_{primary}$ = 0.93 [Btu/lb$_m$-F]	$cp_{secondary}$ = 0.935 [Btu/lb$_m$-F]	dT1 = 16
dT2 = 8	$D_{hydraulic}$ = 0.016 [ft]	e = 0.00015
η_{pump} = 0.75	f = 0.01288	$Flow_{Area}$ = 0.84 [ft^2]
g = 32.2 [ft/s^2]	G_{pri} = 163.8 [lb$_m$/s-ft^2]]	G_{sec} = 90.51 [lb$_m$/s-ft^2]]
hl_{maj} = 21.43 [ft]	hl_{min} = 29.4 [ft]	h_{pri} = 1229 [Btu/hr-ft^2-F]

K_{total} = 4.95
K_{valve} = 0.15
$Length_{ft}$ = 3.847 [ft]
$Length_{in}$ = 46.16 [in]
LMTD = 11.54 [F]
μ_{pg} = 0.0024 [lb_m/ft-s]
$\dot{m}_{primary}$ = 495290 [lb_m/hr]
$\dot{m}_{secondary}$ = 273690 [lb_m/hr]
ν_{pri} = 78.67
ν_{sec} = 52.87
n_b = 4
N_{plates} = 140
N_{seg} = 25
$Plate_{Gap}$ = 0.008 [ft]
$Plate_{Width}$ = 1.5 [ft]
Pr_{pg} = 25
p_{hp} = 486.4 [hp]
$\dot{Q}_{Btu}$ = 4.606E+06 [Btu/hr]
$\dot{Q}_{kW}$ = 1350 [kW]
Re_{pg} = 1.048E+06
$Re_{plate,pri}$ = 1092
$Re_{plate,sec}$ = 603.4
ρ_{pg} = 64.32 [lb_m/ft^3]
seg_D = 24 [in]
$seg_{D,ft}$ = 2 [ft]
seg_V = 19.56 [ft/s]
SG_{pg} = 1.031
$Total_{Area}$ = 807.8 [ft^2]
$Total_{flow,cfs}$ = 61.44 [ft^3/s]
$Total_{flow,rate,GPM}$ = 27576 [gpm]
$Total_{Head,Loss}$ = 50.82 [ft]
$Total_l$ = 560 [ft]
$T_{primary,cold}$ = 44 [F]
$T_{primary,hot}$ = 54 [F]
$T_{secondary,cold}$ = 52 [F]
$T_{secondary,hot}$ = 70 [F]
$UA_{required}$ = 399097 [Btu/hr-F]
$U_{overall}$ = 494

No unit problems were detected.

Parametric Table: Table 1

	seg_D [in]	seg_V [ft/s]	p_{hp} [hp]	Re_{pg}	hl_{maj} [ft]
Run 1	15	50.07	3455	1.677E+06	168.3
Run 2	17	38.98	2040	1.480E+06	96.36
Run 3	19	31.2	1281	1.324E+06	59.02
Run 4	21	25.54	844.9	1.198E+06	38.13
Run 5	23	21.29	579.8	1.094E+06	25.73
Run 6	25	18.02	411.1	1.006E+06	17.99
Run 7	27	15.45	299.7	931770	12.96
Run 8	29	13.39	223.7	867510	9.582
Run 9	31	11.72	170.4	811542	7.24
Run 10	33	10.34	132.1	762357	5.575
Run 11	35	9.196	104	718794	4.365

Parametric Table: Table 2

	N_{plates}	$Length_{in}$ [in]	$U_{overall}$	$Re_{plate,pri}$
Run 1	100	51.58	619	1529
Run 2	110	49.98	580.7	1390
Run 3	120	48.57	547.8	1274
Run 4	130	47.3	519.2	1176
Run 5	140	46.16	494	1092
Run 6	150	45.12	471.7	1019
Run 7	160	44.17	451.8	955.4
Run 8	170	43.3	433.8	899.2
Run 9	180	42.49	417.5	849.3
Run 10	190	41.74	402.6	804.6
Run 11	200	41.04	389	764.3

Parametric Table: Table 3

	$T_{primary,cold}$ [F]	$Length_{in}$ [in]	LMTD [F]	$UA_{required}$ [Btu/hr-F]
Run 1	30	20.66	25.79	178579

Parametric Table: Table 3

	$T_{primary,cold}$ [F]	$Length_{in}$ [in]	LMTD [F]	$UA_{required}$ [Btu/hr-F]
Run 2	32	*22.41*	*23.78*	*193732*
Run 3	34	*24.49*	*21.76*	*211727*
Run 4	36	*27*	*19.73*	*233457*
Run 5	38	*30.1*	*17.7*	*260242*
Run 6	40	*34.02*	*15.66*	*294121*
Run 7	42	*39.14*	*13.61*	*338433*
Run 8	44	*46.16*	*11.54*	*399097*
Run 9	46	*56.43*	*9.442*	*487853*
Run 10	48	*73.16*	*7.282*	*632553*
Run 11	50	*107.2*	*4.971*	*926674*

Parametric Table: Table 4

	$T_{secondary,cold}$ [F]	$Length_{in}$ [in]	LMTD [F]	$UA_{required}$ [Btu/hr-F]
Run 1	45	*146.3*	*3.641*	*1.265E+06*
Run 2	47	*86.53*	*6.157*	*748095*
Run 3	49	*63.63*	*8.372*	*550160*
Run 4	51	*50.76*	*10.5*	*438821*
Run 5	53	*42.35*	*12.58*	*366186*
Run 6	55	*36.4*	*14.64*	*314686*
Run 7	57	*31.94*	*16.68*	*276126*
Run 8	59	*28.47*	*18.72*	*246112*
Run 9	61	*25.68*	*20.74*	*222055*
Run 10	63	*23.4*	*22.77*	*202326*
Run 11	65	*21.5*	*24.79*	*185845*

```
{ ME 4315 Project 2) }
{ BWRX-300  EES Modeling}


$UnitSystem SI K kPa kJ

{known parameters (from published GE-Hitachi Data + traditional set points }

Q_reactor = 870000   [kW]
P_reactor = 7200     [kPa]
W_elec_consume_given = 30000 [kW]
eta_gen = 0.98

T_core_in  = 543  [K] "typical BWR inlet"
T_core_out = 561  [K] "typical BWR outlet"

P_cond = 7 [kPa] "BWR industry default is between 7-8 kPa"

eta_pump = 0.82 "Standard range for large industrial feedwater pumps"
eta_HP   = 0.88 "HP Turbine Efficiency from GE data"
eta_LP1  = 0.90 "LP Turbine Stage 1 Efficiency from GE data"
eta_LP2  = 0.90 "LP Turbine Stage 2 Efficiency from GE data"

DeltaT_reheat = 35 [K] "typical BWR moisture separator reheater range (30–40°C or K)"


{states for thermodynamic analysis}

{State 12 to Condenser Outlet }

P12 = P_cond
x12 = 0
h12 = Enthalpy(Steam, P=P12, x=x12)
s12 = Entropy(Steam, P=P12, x=x12)
T12 = Temperature(Steam, P=P12, x=x12)
v12 = Volume(Steam, P=P12, x=x12)

{ Pump : State 12 to 1}
P1 = P_reactor
w_pump_ideal = v12*(P1 - P12)
w_pump = w_pump_ideal/eta_pump

h1 = h12 + w_pump
T1 = Temperature(Steam, P=P1, h=h1)
s1 = Entropy(Steam, P=P1, h=h1)


{Reactor Heating: 1 to 3}

P3 = P_reactor
T3 = T_core_out
h3 = Enthalpy(Steam, P=P3, T=T3)
s3 = Entropy(Steam, P=P3, T=T3)


{High Pressure Turbine :  3 to 4 }
```

```
P4 = 1700 [kPa]
h4s = Enthalpy(Steam, P=P4, s=s3)
w_HP = eta_HP*(h3 - h4s)

h4 = h3 - w_HP
T4 = Temperature(Steam, P=P4, h=h4)
s4 = Entropy(Steam, P=P4, h=h4)
x4 = Quality(Steam, P=P4, h=h4)


{Moisture Separator : 4 to 6 }
{ bwrx-300 low pressure turbine is designed for DRY steam }

P6 = P4
h6 = h4
s6 = s4
T6 = T4
x6 = x4



{ Reheater: 6 to 7}

P7 = P6
T7 = T6 + DeltaT_reheat
h7 = Enthalpy(Steam, P=P7, T=T7)
s7 = Entropy(Steam, P=P7, h=h7)

T_source_reheat = (T6 + T7)/2




{Low Pressure Turbine : 7 to 8}

P8 = 250 [kPa]
h8s = Enthalpy(Steam, P=P8, s=s7)
w_LP1 = eta_LP1*(h7 - h8s)

h8 = h7 - w_LP1
T8 = Temperature(Steam, P=P8, h=h8)
s8 = Entropy(Steam, P=P8, h=h8)
x8 = Quality(Steam, P=P8, h=h8)


{Low Pressure Turbine : 8 to10 }
P10 = P_cond
h10s = Enthalpy(Steam, P=P10, s=s8)
w_LP2 = eta_LP2*(h8 - h10s)

h10 = h8 - w_LP2
T10 = Temperature(Steam, P=P10, h=h10)
s10 = Entropy(Steam, P=P10, h=h10)
x10 = Quality(Steam, P=P10, h=h10)
```

```

{Mass (steam) Flow Calc}

m_dot_steam = Q_reactor / (h3 - h1)


{Energy Balance}

Q_core = m_dot_steam*(h3 - h1)
Q_reheat = m_dot_steam*(h7 - h6)
Q_in_total = Q_core + Q_reheat

w_turbine_total = w_HP + w_LP1 + w_LP2
w_net = w_turbine_total - w_pump

W_turbine_gross = m_dot_steam*w_turbine_total
W_pump_consumed = m_dot_steam*w_pump
W_net_mech = m_dot_steam*w_net

W_elec_gross = eta_gen*W_net_mech
W_elec_net = W_elec_gross - W_elec_consume_given

Q_condenser = m_dot_steam*(h10 - h12)

eta_thermal = W_net_mech / Q_in_total
eta_thermal_pct = 100*eta_thermal

eta_plant_net = W_elec_net / Q_in_total
eta_plant_net_pct = 100*eta_plant_net

W_check = Q_in_total - Q_condenser
FirstLaw_residual = W_net_mech - W_check



{Exergy Analysis}
T0 = 298 [K]
P0 = 101.3 [kPa]

h0 = Enthalpy(Water, T=T0, P=P0)
s0 = Entropy(Water, T=T0, P=P0)

{ specific flow exergy at key states }

ex1  = (h1  - h0) - T0*(s1  - s0)
ex3  = (h3  - h0) - T0*(s3  - s0)
ex4  = (h4  - h0) - T0*(s4  - s0)
ex6  = (h6  - h0) - T0*(s6  - s0)
ex7  = (h7  - h0) - T0*(s7  - s0)
ex8  = (h8  - h0) - T0*(s8  - s0)
ex10 = (h10 - h0) - T0*(s10 - s0)
ex12 = (h12 - h0) - T0*(s12 - s0)

{ exergy rates (kW) }

Ex_1 = m_dot_steam*ex1
```

```
Ex_3  = m_dot_steam*ex3
Ex_4  = m_dot_steam*ex4
Ex_6  = m_dot_steam*ex6
Ex_7  = m_dot_steam*ex7
Ex_8  = m_dot_steam*ex8
Ex_10 = m_dot_steam*ex10
Ex_12 = m_dot_steam*ex12
{ mechanical work rates }
W_HP_mech  = m_dot_steam*w_HP
W_LP1_mech = m_dot_steam*w_LP1
W_LP2_mech = m_dot_steam*w_LP2
{ turbine, pump, condenser exergy destruction }
Ex_dest_HP   = Ex_3  - Ex_4  - W_HP_mech
Ex_dest_LP1  = Ex_7  - Ex_8  - W_LP1_mech
Ex_dest_LP2  = Ex_8  - Ex_10 - W_LP2_mech
Ex_dest_pump = Ex_12 + W_pump_consumed - Ex_1
{ condenser: split into loss to cooling water + small internal dest }
T_cond_avg   = (T10 + T12)/2
Ex_loss_cond = Q_condenser*(1 - T0/T_cond_avg)
Ex_dest_cond = Ex_10 - Ex_12 - Ex_loss_cond
{ exergy of heat inputs }
Ex_in_reactor = Q_reactor*(1 - T0/T3)
Ex_in_reheat  = Q_reheat *(1 - T0/T_source_reheat)
Ex_in_total   = Ex_in_reactor + Ex_in_reheat
{ exergy destruction in reactor core and reheater }
Ex_dest_reactor = Ex_in_reactor - (Ex_3 - Ex_1)
Ex_dest_reheat  = Ex_in_reheat  - (Ex_7 - Ex_6)
{ generator irreversibility and house-load exergy use }
Ex_dest_gen   = W_net_mech*(1 - eta_gen)   {losses in generator}
Ex_loss_house = W_elec_consume_given          {aux electrical usage}
{ total "lost" or destroyed exergy }
Ex_total_losses = Ex_dest_HP + Ex_dest_LP1 + Ex_dest_LP2 + Ex_dest_pump + Ex_dest_cond + Ex_dest_reactor +
   Ex_dest_reheat + Ex_dest_gen + Ex_loss_cond + Ex_loss_house
{ exergy efficiency based on net electricity to grid }
eta_exergy     = W_elec_net / Ex_in_total
eta_exergy_pct = 100*eta_exergy
{ exergy balance – should be ~0 }
Ex_balance = Ex_in_total - (W_elec_net + Ex_total_losses)
```

```



{Cooling Loop - tertiary}
{ Simple once-through cooling water }

T_cw_in   = 303  [K]        {30 °C cooling water inlet}
DeltaT_cw = 10   [K]        {warms up by 10 K across condenser}
T_cw_out  = T_cw_in + DeltaT_cw
T_cw_avg  = (T_cw_in + T_cw_out)/2

cp_cw = Cp(Water,   T=T_cw_avg, P=P0)       {kJ/kg-K}
v_cw  = Volume(Water, T=T_cw_avg, P=P0)     {m^3/kg}

{ Q_condenser is already in kW from main cycle }
m_dot_cw = Q_condenser / (cp_cw*DeltaT_cw)  {kg/s}
V_dot_cw = m_dot_cw * v_cw                 {m^3/s}




{efficiency summaries + exergy buckets (for checks and report)}

{ Thermal efficiencies }

eta_th_core_only      = W_net_mech / Q_core
eta_th_core_only_pct  = 100*eta_th_core_only

eta_th_total          = W_net_mech / Q_in_total
eta_th_total_pct      = 100*eta_th_total

eta_plant_net_core      = W_elec_net / Q_core
eta_plant_net_core_pct  = 100*eta_plant_net_core


{ Exergy buckets }

Ex_dest_reactor_bucket = Ex_dest_reactor
Ex_dest_reheat_bucket  = Ex_dest_reheat
Ex_dest_HP_bucket      = Ex_dest_HP
Ex_dest_LP1_bucket     = Ex_dest_LP1
Ex_dest_LP2_bucket     = Ex_dest_LP2
Ex_dest_pump_bucket    = Ex_dest_pump
Ex_dest_cond_bucket    = Ex_dest_cond
Ex_dest_gen_bucket     = Ex_dest_gen
Ex_dest_house_bucket   = Ex_loss_house
Ex_loss_to_cooling     = Ex_loss_cond

Ex_total_losses_check = Ex_dest_reactor_bucket + Ex_dest_reheat_bucket + Ex_dest_HP_bucket + Ex_dest_LP1_bucket +
 Ex_dest_LP2_bucket + Ex_dest_pump_bucket + Ex_dest_cond_bucket + Ex_dest_gen_bucket + Ex_dest_house_bucket +
 Ex_loss_to_cooling


{ Exergy balance quality check }

Ex_balance_summary = Ex_in_total - (W_elec_net + Ex_total_losses_check)
```

```
{House load fraction}
house_load_fraction_elec = W_elec_consume_given / W_elec_gross
house_load_fraction_elec_pct = 100*house_load_fraction_elec
{made arrays for reporting and organaztional purposes}
{Pressure}
P[1]  = P1
P[3]  = P3
P[4]  = P4
P[6]  = P6
P[7]  = P7
P[8]  = P8
P[10] = P10
P[12] = P12
{Temperature}
T[1]  = T1
T[3]  = T3
T[4]  = T4
T[6]  = T6
T[7]  = T7
T[8]  = T8
T[10] = T10
T[12] = T12
{Enthalpy}
h[1]  = h1
h[3]  = h3
h[4]  = h4
h[6]  = h6
h[7]  = h7
h[8]  = h8
h[10] = h10
h[12] = h12
{Entropy}
s[1]  = s1
s[3]  = s3
s[4]  = s4
s[6]  = s6
s[7]  = s7
s[8]  = s8
s[10] = s10
s[12] = s12
{Quality}
x[1]  = 0
x[3]  = 1
x[4]  = x4
x[6]  = x6
x[7]  = 1
```

```
x[8]  = x8
x[10] = x10
x[12] = x12

{Exergy}
ex[1]  = ex1
ex[3]  = ex3
ex[4]  = ex4
ex[6]  = ex6
ex[7]  = ex7
ex[8]  = ex8
ex[10] = ex10
ex[12] = ex12
```

$Q_{reactor} = 870000$ [kW]

$P_{reactor} = 7200$ [kPa]

$W_{elec,consume,given} = 30000$ [kW]

$\eta_{gen} = 0.98$

$T_{core,in} = 543$ [K] typical BWR inlet

$T_{core,out} = 561$ [K] typical BWR outlet

$P_{cond} = 7$ [kPa] BWR industry default is between 7-8 kPa

$\eta_{pump} = 0.82$ Standard range for large industrial feedwater pumps

$\eta_{HP} = 0.88$ HP Turbine Efficiency from GE data

$\eta_{LP1} = 0.9$ LP Turbine Stage 1 Efficiency from GE data

$\eta_{LP2} = 0.9$ LP Turbine Stage 2 Efficiency from GE data

$\delta T_{reheat} = 35$ [K]

typical BWR moisture separator reheater range (30–40°C or K)

$P12 = P_{cond}$

$x12 = 0$

$h12 = \mathbf{h}(\text{Steam}, P = P12, x = x12)$

$s12 = \mathbf{s}(\text{Steam}, P = P12, x = x12)$

$T12 = \mathbf{T}(\text{Steam}, P = P12, x = x12)$

$v12 = \mathbf{v}(\text{Steam}, P = P12, x = x12)$

$P1 = P_{reactor}$

$w_{pump,ideal} = v12 \cdot (P1 - P12)$

$w_{pump} = \dfrac{w_{pump,ideal}}{\eta_{pump}}$

$h1 = h12 + w_{pump}$

$T1 = \mathbf{T}(Steam, P = P1, h = h1)$

$s1 = \mathbf{s}(Steam, P = P1, h = h1)$

$P3 = P_{reactor}$

$T3 = T_{core,out}$

$h3 = \mathbf{h}(Steam, P = P3, T = T3)$

$s3 = \mathbf{s}(Steam, P = P3, T = T3)$

$P4 = 1700$ [kPa]

$h4s = \mathbf{h}(Steam, P = P4, s = s3)$

$w_{HP} = \eta_{HP} \cdot (h3 - h4s)$

$h4 = h3 - w_{HP}$

$T4 = \mathbf{T}(Steam, P = P4, h = h4)$

$s4 = \mathbf{s}(Steam, P = P4, h = h4)$

$x4 = \mathbf{x}(Steam, P = P4, h = h4)$

$P6 = P4$

$h6 = h4$

$s6 = s4$

$T6 = T4$

$x6 = x4$

$P7 = P6$

$T7 = T6 + \delta T_{reheat}$

$h7 = \mathbf{h}(Steam, P = P7, T = T7)$

$s7 = \mathbf{s}(Steam, P = P7, h = h7)$

$T_{source,reheat} = \dfrac{T6 + T7}{2}$

$P8 = 250$ [kPa]

$$h8s = \mathbf{h}(Steam, P = P8, s = s7)$$

$$w_{LP1} = \eta_{LP1} \cdot (h7 - h8s)$$

$$h8 = h7 - w_{LP1}$$

$$T8 = \mathbf{T}(Steam, P = P8, h = h8)$$

$$s8 = \mathbf{s}(Steam, P = P8, h = h8)$$

$$x8 = \mathbf{x}(Steam, P = P8, h = h8)$$

$$P10 = P_{cond}$$

$$h10s = \mathbf{h}(Steam, P = P10, s = s8)$$

$$w_{LP2} = \eta_{LP2} \cdot (h8 - h10s)$$

$$h10 = h8 - w_{LP2}$$

$$T10 = \mathbf{T}(Steam, P = P10, h = h10)$$

$$s10 = \mathbf{s}(Steam, P = P10, h = h10)$$

$$x10 = \mathbf{x}(Steam, P = P10, h = h10)$$

$$\dot{m}_{steam} = \frac{Q_{reactor}}{h3 - h1}$$

$$Q_{core} = \dot{m}_{steam} \cdot (h3 - h1)$$

$$Q_{reheat} = \dot{m}_{steam} \cdot (h7 - h6)$$

$$Q_{in,total} = Q_{core} + Q_{reheat}$$

$$w_{turbine,total} = w_{HP} + w_{LP1} + w_{LP2}$$

$$w_{net} = w_{turbine,total} - w_{pump}$$

$$W_{turbine,gross} = \dot{m}_{steam} \cdot w_{turbine,total}$$

$$W_{pump,consumed} = \dot{m}_{steam} \cdot w_{pump}$$

$$W_{net,mech} = \dot{m}_{steam} \cdot w_{net}$$

$$W_{elec,gross} = \eta_{gen} \cdot W_{net,mech}$$

$$W_{elec,net} = W_{elec,gross} - W_{elec,consume,given}$$

$$Q_{condenser} = \dot{m}_{steam} \cdot (h10 - h12)$$

$$\eta_{thermal} = \frac{W_{net,mech}}{Q_{in,total}}$$

$\eta_{thermal,pct} = 100 \cdot \eta_{thermal}$

$\eta_{plant,net} = \dfrac{W_{elec,net}}{Q_{in,total}}$

$\eta_{plant,net,pct} = 100 \cdot \eta_{plant,net}$

$W_{check} = Q_{in,total} - Q_{condenser}$

$FirstLaw_{residual} = W_{net,mech} - W_{check}$

$T0 = 298$ [K]

$P0 = 101.3$ [kPa]

$h0 = \mathbf{h}(Water, T = T0, P = P0)$

$s0 = \mathbf{s}(Water, T = T0, P = P0)$

$ex1 = h1 - h0 - T0 \cdot (s1 - s0)$

$ex3 = h3 - h0 - T0 \cdot (s3 - s0)$

$ex4 = h4 - h0 - T0 \cdot (s4 - s0)$

$ex6 = h6 - h0 - T0 \cdot (s6 - s0)$

$ex7 = h7 - h0 - T0 \cdot (s7 - s0)$

$ex8 = h8 - h0 - T0 \cdot (s8 - s0)$

$ex10 = h10 - h0 - T0 \cdot (s10 - s0)$

$ex12 = h12 - h0 - T0 \cdot (s12 - s0)$

$Ex_1 = \dot{m}_{steam} \cdot ex1$

$Ex_3 = \dot{m}_{steam} \cdot ex3$

$Ex_4 = \dot{m}_{steam} \cdot ex4$

$Ex_6 = \dot{m}_{steam} \cdot ex6$

$Ex_7 = \dot{m}_{steam} \cdot ex7$

$Ex_8 = \dot{m}_{steam} \cdot ex8$

$Ex_{10} = \dot{m}_{steam} \cdot ex10$

$Ex_{12} = \dot{m}_{steam} \cdot ex12$

$W_{HP,mech} = \dot{m}_{steam} \cdot w_{HP}$

$W_{LP1,mech} = \dot{m}_{steam} \cdot w_{LP1}$

$$Ex_{dest,HP} = Ex_3 - Ex_4 - W_{HP,mech}$$

$$Ex_{dest,LP1} = Ex_7 - Ex_8 - W_{LP1,mech}$$

$$Ex_{dest,LP2} = Ex_8 - Ex_{10} - W_{LP2,mech}$$

$$Ex_{dest,pump} = Ex_{12} + W_{pump,consumed} - Ex_1$$

$$T_{cond,avg} = \frac{T10 + T12}{2}$$

$$Ex_{loss,cond} = Q_{condenser} \cdot \left[1 - \frac{T0}{T_{cond,avg}}\right]$$

$$Ex_{dest,cond} = Ex_{10} - Ex_{12} - Ex_{loss,cond}$$

$$Ex_{in,reactor} = Q_{reactor} \cdot \left[1 - \frac{T0}{T3}\right]$$

$$Ex_{in,reheat} = Q_{reheat} \cdot \left[1 - \frac{T0}{T_{source,reheat}}\right]$$

$$Ex_{in,total} = Ex_{in,reactor} + Ex_{in,reheat}$$

$$Ex_{dest,reactor} = Ex_{in,reactor} - (Ex_3 - Ex_1)$$

$$Ex_{dest,reheat} = Ex_{in,reheat} - (Ex_7 - Ex_6)$$

$$Ex_{dest,gen} = W_{net,mech} \cdot (1 - \eta_{gen})$$

$$Ex_{loss,house} = W_{elec,consume,given}$$

$$Ex_{total,losses} = Ex_{dest,HP} + Ex_{dest,LP1} + Ex_{dest,LP2} + Ex_{dest,pump} + Ex_{dest,cond} + Ex_{dest,reactor} + Ex_{dest,reheat} + Ex_{dest,gen} + Ex_{loss,cond} + Ex_{loss,house}$$

$$\eta_{exergy} = \frac{W_{elec,net}}{Ex_{in,total}}$$

$$\eta_{exergy,pct} = 100 \cdot \eta_{exergy}$$

$$Ex_{balance} = Ex_{in,total} - (W_{elec,net} + Ex_{total,losses})$$

$$T_{cw,in} = 303 \ [K]$$

$$\delta T_{cw} = 10 \ [K]$$

$$T_{cw,out} = T_{cw,in} + \delta T_{cw}$$

$$T_{cw,avg} = \frac{T_{cw,in} + T_{cw,out}}{2}$$

$$cp_{cw} = \mathbf{Cp}(Water, T = T_{cw,avg}, P = P0)$$

$v_{cw} = \mathbf{v}(Water, T = T_{cw,avg}, P = P0)$

$\dot{m}_{cw} = \dfrac{Q_{condenser}}{cp_{cw} \cdot \delta T_{cw}}$

$\dot{V}_{cw} = \dot{m}_{cw} \cdot v_{cw}$

$\eta_{th,core,only} = \dfrac{W_{net,mech}}{Q_{core}}$

$\eta_{th,core,only,pct} = 100 \cdot \eta_{th,core,only}$

$\eta_{th,total} = \dfrac{W_{net,mech}}{Q_{in,total}}$

$\eta_{th,total,pct} = 100 \cdot \eta_{th,total}$

$\eta_{plant,net,core} = \dfrac{W_{elec,net}}{Q_{core}}$

$\eta_{plant,net,core,pct} = 100 \cdot \eta_{plant,net,core}$

$Ex_{dest,reactor,bucket} = Ex_{dest,reactor}$

$Ex_{dest,reheat,bucket} = Ex_{dest,reheat}$

$Ex_{dest,HP,bucket} = Ex_{dest,HP}$

$Ex_{dest,LP1,bucket} = Ex_{dest,LP1}$

$Ex_{dest,LP2,bucket} = Ex_{dest,LP2}$

$Ex_{dest,pump,bucket} = Ex_{dest,pump}$

$Ex_{dest,cond,bucket} = Ex_{dest,cond}$

$Ex_{dest,gen,bucket} = Ex_{dest,gen}$

$Ex_{dest,house,bucket} = Ex_{loss,house}$

$Ex_{loss,to,cooling} = Ex_{loss,cond}$

$Ex_{total,losses,check} = Ex_{dest,reactor,bucket} + Ex_{dest,reheat,bucket} + Ex_{dest,HP,bucket} + Ex_{dest,LP1,bucket} + Ex_{dest,LP2,bucket} + Ex_{dest,pump,bucket} + Ex_{dest,cond,bucket} + Ex_{dest,gen,bucket} + Ex_{dest,house,bucket} + Ex_{loss,to,cooling}$

$Ex_{balance,summary} = Ex_{in,total} - (W_{elec,net} + Ex_{total,losses,check})$

$house_{load,fraction,elec} = \dfrac{W_{elec,consume,given}}{W_{elec,gross}}$

$house_{load,fraction,elec,pct} = 100 \cdot house_{load,fraction,elec}$

$P_1 = P1$

P_3 = P3

P_4 = P4

P_6 = P6

P_7 = P7

P_8 = P8

P_{10} = P10

P_{12} = P12

T_1 = T1

T_3 = T3

T_4 = T4

T_6 = T6

T_7 = T7

T_8 = T8

T_{10} = T10

T_{12} = T12

h_1 = h1

h_3 = h3

h_4 = h4

h_6 = h6

h_7 = h7

h_8 = h8

h_{10} = h10

h_{12} = h12

s_1 = s1

s_3 = s3

s_4 = s4

s_6 = s6

s_7 = s7

s_8 = s8

s_{10} = s10

s_{12} = s12

x_1 = 0

x_3 = 1

x_4 = x4

x_6 = x6

x_7 = 1

x_8 = x8

x_{10} = x10

x_{12} = x12

ex_1 = ex1

ex_3 = ex3

ex_4 = ex4

ex_6 = ex6

ex_7 = ex7

ex_8 = ex8

ex_{10} = ex10

ex_{12} = ex12

SOLUTION

Unit Settings: SI K kPa kJ mass deg

cp_{cw} = 4.179 [kJ/(kg*K)]
δT_{cw} = 10 [K]
δT_{reheat} = 35 [K]
η_{exergy} = 0.6469 [-]
$\eta_{exergy,pct}$ = 64.69 [%]
η_{gen} = 0.98 [-]
η_{HP} = 0.88 [-]
η_{LP1} = 0.9 [-]
η_{LP2} = 0.9 [-]
$\eta_{plant,net}$ = 0.2978 [-]
$\eta_{plant,net,core}$ = 0.3378 [-]
$\eta_{plant,net,core,pct}$ = 33.78 [%]
η = 29.78 [-]

$\eta_{thermal}$ = 0.3349 [-]
$\eta_{thermal,pct}$ = 33.49 [%]
$\eta_{th,core,only}$ = 0.3799 [-]
$\eta_{th,core,only,pct}$ = 37.99 [%]
$\eta_{th,total}$ = 0.3349 [-]
$\eta_{th,total,pct}$ = 33.49 [%]
ex1 = 8.577 [kJ/kg]
ex10 = 90.11 [kJ/kg]
ex12 = 1.267 [kJ/kg]
ex3 = 1046 [kJ/kg]
ex4 = 797 [kJ/kg]
ex6 = 797 [kJ/kg]
ex7 = 930 [kJ/kg]
ex8 = 581.1 [kJ/kg]
Ex_1 = 2872 [kW] {2.872 [MW]}
Ex_{10} = 30169 [kW] {30.17 [MW]}
Ex_{12} = 424.1 [kW] {0.4241 [MW]}
Ex_3 = 350308 [kW] {350.3 [MW]}
Ex_4 = 266858 [kW] {266.9 [MW]}
Ex_6 = 266858 [kW] {266.9 [MW]}
Ex_7 = 311385 [kW] {311.4 [MW]}
Ex_8 = 194573 [kW] {194.6 [MW]}
$Ex_{balance}$ = -2.842E-14 [kW] {-2.842E-17 [MW]}
$Ex_{balance,summary}$ = -2.842E-14 [kW] {-2.842E-17 [MW]}
$Ex_{dest,cond}$ = 0.7642 [kW] {0.0007642 [MW]}
$Ex_{dest,cond,bucket}$ = 0.7642 [kW] {0.0007642 [MW]}
$Ex_{dest,gen}$ = 6610 [kW] {6.61 [MW]}
$Ex_{dest,gen,bucket}$ = 6610 [kW] {6.61 [MW]}
$Ex_{dest,house,bucket}$ = 30000 [kW] {30 [MW]}
$Ex_{dest,HP}$ = 6545 [kW] {6.545 [MW]}
$Ex_{dest,HP,bucket}$ = 6545 [kW] {6.545 [MW]}
$Ex_{dest,LP1}$ = 8919 [kW] {8.919 [MW]}
$Ex_{dest,LP1,bucket}$ = 8919 [kW] {8.919 [MW]}
$Ex_{dest,LP2}$ = 15767 [kW] {15.77 [MW]}
$Ex_{dest,LP2,bucket}$ = 15767 [kW] {15.77 [MW]}
$Ex_{dest,pump}$ = 511.4 [kW] {0.5114 [MW]}
$Ex_{dest,pump,bucket}$ = 511.4 [kW] {0.5114 [MW]}
$Ex_{dest,reactor}$ = 60425 [kW] {60.42 [MW]}
$Ex_{dest,reactor,bucket}$ = 60425 [kW] {60.42 [MW]}
$Ex_{dest,reheat}$ = 1902 [kW] {1.902 [MW]}
$Ex_{dest,reheat,bucket}$ = 1902 [kW] {1.902 [MW]}
$Ex_{in,reactor}$ = 407861 [kW] {407.9 [MW]}
$Ex_{in,reheat}$ = 46430 [kW] {46.43 [MW]}
$Ex_{in,total}$ = 454291 [kW] {454.3 [MW]}
$Ex_{loss,cond}$ = 29745 [kW] {29.74 [MW]}
$Ex_{loss,house}$ = 30000 [kW] {30 [MW]}
$Ex_{loss,to,cooling}$ = 29745 [kW] {29.74 [MW]}
$Ex_{total,losses}$ = 160424 [kW] {160.4 [MW]}
$Ex_{total,losses,check}$ = 160424 [kW] {160.4 [MW]}
$FirstLaw_{residual}$ = -5.684E-14
h0 = 104.3 [kJ/kg]
h1 = 172.2 [kJ/kg]
h10 = 2123 [kJ/kg]
h10s = 2074 [kJ/kg]
h12 = 163.4 [kJ/kg]

h4 = 2541 [kJ/kg]
h4s = 2510 [kJ/kg]
h6 = 2541 [kJ/kg]
h7 = 2889 [kJ/kg]
h8 = 2567 [kJ/kg]
h8s = 2531 [kJ/kg]
$house_{load,fraction,elec}$ = 0.09263 [-]
$house_{load,fraction,elec,pct}$ = 9.263 [%]
$\dot{m}_{cw}$ = 15701 [kg/s]
$\dot{m}_{steam}$ = 334.8 [kg/s]
P0 = 101.3 [kPa]
P1 = 7200 [kPa]
P10 = 7 [kPa]
P12 = 7 [kPa]
P3 = 7200 [kPa]
P4 = 1700 [kPa]
P6 = 1700 [kPa]
P7 = 1700 [kPa]
P8 = 250 [kPa]
P_{cond} = 7 [kPa]
$P_{reactor}$ = 7200 [kPa]
$Q_{condenser}$ = 656203 [kW] {656.2 [MW]}
Q_{core} = 870000 [kW] {870 [MW]}
$Q_{in,total}$ = 986679 [kW] {986.7 [MW]}
$Q_{reactor}$ = 870000 [kW] {870 [MW]}
Q_{reheat} = 116679 [kW] {116.7 [MW]}
s0 = 0.3651 [kJ/(kg·K)]
s1 = 0.5642 [kJ/(kg·K)]
s10 = 6.838 [kJ/(kg·K)]
s12 = 0.559 [kJ/(kg·K)]
s3 = 5.801 [kJ/(kg·K)]
s4 = 5.867 [kJ/(kg·K)]
s6 = 5.867 [kJ/(kg·K)]
s7 = 6.59 [kJ/(kg·K)]
s8 = 6.68 [kJ/(kg·K)]
T0 = 298 [K]
T1 = 312.7 [K]
T10 = 312.1 [K]
T12 = 312.1 [K]
T3 = 561 [K]
T4 = 477.5 [K]
T6 = 477.5 [K]
T7 = 512.5 [K]
T8 = 400.6 [K]
$T_{cond,avg}$ = 312.1 [K]
$T_{core,in}$ = 543 [K]
$T_{core,out}$ = 561 [K]
$T_{cw,avg}$ = 308 [K]
$T_{cw,in}$ = 303 [K]
$T_{cw,out}$ = 313 [K]
$T_{source,reheat}$ = 495 [K]
v12 = 0.001008 [m^3/kg]
v_{cw} = 0.001006 [m^3/kg]
$\dot{V}_{cw}$ = 15.79 [m^3/s]
W = 330476 [kW] {330.5 [MW]}

$W_{elec,gross}$ = 323867 [kW] {323.9 [MW]}
$W_{elec,net}$ = 293867 [kW] {293.9 [MW]}
w_{HP} = 229.7 [kJ/kg]
$W_{HP,mech}$ = 76905 [kW] {76.9 [MW]}
w_{LP1} = 322.2 [kJ/kg]
$W_{LP1,mech}$ = 107893 [kW] {107.9 [MW]}
w_{LP2} = 443.9 [kJ/kg]
$W_{LP2,mech}$ = 148637 [kW] {148.6 [MW]}
w_{net} = 987 [kJ/kg]
$W_{net,mech}$ = 330476 [kW] {330.5 [MW]}
w_{pump} = 8.838 [kJ/kg]
$W_{pump,consumed}$ = 2959 [kW] {2.959 [MW]}
$w_{pump,ideal}$ = 7.247 [kJ/kg]
$W_{turbine,gross}$ = 333435 [kW] {333.4 [MW]}
$w_{turbine,total}$ = 995.9 [kJ/kg]
x10 = 0.8138 [-]
x12 = 0 [-]
x4 = 0.8681 [-]
x6 = 0.8681 [-]
x8 = 0.9315 [-]

7 potential unit problems were detected.

Arrays Table: Main

	s_i [kJ/kg-K]	T_i [K]	x_i [-]	ex_i [kJ/kg]	h_i [kJ/kg]	P_i [kPa]
1	0.5642	312.7	0	8.577	172.2	7200
2						
3	5.801	561	1	1046	2771	7200
4	5.867	477.5	0.8681	797	2541	1700
5						
6	5.867	477.5	0.8681	797	2541	1700
7	6.59	512.5	1	930	2889	1700
8	6.68	400.6	0.9315	581.1	2567	250
9						
10	6.838	312.1	0.8138	90.11	2123	7
11						
12	0.559	312.1	0	1.267	163.4	7

There is a total of 194 equations in the Main program.

Block	Rel. Res.	Abs. Res.	Units	Calls	Time(ms)	Equations
0	0.000E+00	0.000E+00	OK	1	0	**Q_reactor**=870000[kW]
0	0.000E+00	0.000E+00	OK	1	0	**P_reactor**=7200[kPa]
0	0.000E+00	0.000E+00	OK	1	0	**W_elec_consume_given**=30000[kW]
0	0.000E+00	0.000E+00	OK	1	0	**eta_gen**=0.98
0	0.000E+00	0.000E+00	OK	1	0	**T_core_in**=543[K]
0	0.000E+00	0.000E+00	OK	1	0	**T_core_out**=561[K]
0	0.000E+00	0.000E+00	OK	1	0	**P_cond**=7[kPa]
0	0.000E+00	0.000E+00	OK	1	0	**eta_pump**=0.82
0	0.000E+00	0.000E+00	OK	1	0	**eta_HP**=0.88
0	0.000E+00	0.000E+00	OK	1	0	**eta_LP1**=0.90
0	0.000E+00	0.000E+00	OK	1	0	**eta_LP2**=0.90
0	0.000E+00	0.000E+00	OK	1	0	**DeltaT_reheat**=35[K]
0	0.000E+00	0.000E+00	OK	1	0	**x12**=0

0	0.000E+00	0.000E+00	OK	1	0	**P4**=1700[kPa]
0	0.000E+00	0.000E+00	OK	1	0	**P8**=250[kPa]
0	0.000E+00	0.000E+00	OK	1	0	**T0**=298[K]
0	0.000E+00	0.000E+00	OK	1	0	**P0**=101.3[kPa]
0	0.000E+00	0.000E+00	OK	1	0	**T_cw_in**=303[K]
0	0.000E+00	0.000E+00	OK	1	0	**DeltaT_cw**=10[K]
0	0.000E+00	0.000E+00	OK	1	0	**x[1]**=0
0	0.000E+00	0.000E+00	OK	1	0	**x[3]**=1
0	0.000E+00	0.000E+00	OK	1	0	**x[7]**=1
0	0.000E+00	0.000E+00	OK	1	0	**P12**=P_cond
0	0.000E+00	0.000E+00	OK	1	0	**h12**=Enthalpy(Steam,P=P12,x=x12)
0	0.000E+00	0.000E+00	OK	1	0	**s12**=Entropy(Steam,P=P12,x=x12)
0	0.000E+00	0.000E+00	OK	1	0	**T12**=Temperature(Steam,P=P12,x=x12)
0	0.000E+00	0.000E+00	OK	1	0	**v12**=Volume(Steam,P=P12,x=x12)
0	0.000E+00	0.000E+00	OK	1	0	**P1**=P_reactor
0	0.000E+00	0.000E+00	OK	1	0	**w_pump_ideal**=v12*(P1-P12)
0	0.000E+00	0.000E+00	OK	1	0	**w_pump**=w_pump_ideal/eta_pump
0	0.000E+00	0.000E+00	OK	1	0	**h1**=h12+w_pump
0	0.000E+00	0.000E+00	OK	1	1	**T1**=Temperature(Steam,P=P1,h=h1)
0	0.000E+00	0.000E+00	OK	1	0	**s1**=Entropy(Steam,P=P1,h=h1)
0	0.000E+00	0.000E+00	OK	1	0	**P3**=P_reactor
0	0.000E+00	0.000E+00	OK	1	0	**T3**=T_core_out
0	0.000E+00	0.000E+00	OK	1	0	**h3**=Enthalpy(Steam,P=P3,T=T3)
0	0.000E+00	0.000E+00	OK	1	0	**s3**=Entropy(Steam,P=P3,T=T3)
0	0.000E+00	0.000E+00	OK	1	0	**h4s**=Enthalpy(Steam,P=P4,s=s3)
0	0.000E+00	0.000E+00	OK	1	0	**w_HP**=eta_HP*(h3-h4s)
0	0.000E+00	0.000E+00	OK	1	0	**h4**=h3-w_HP
0	0.000E+00	0.000E+00	OK	1	0	**T4**=Temperature(Steam,P=P4,h=h4)
0	0.000E+00	0.000E+00	OK	1	0	**s4**=Entropy(Steam,P=P4,h=h4)
0	0.000E+00	0.000E+00	OK	1	0	**x4**=Quality(Steam,P=P4,h=h4)
0	0.000E+00	0.000E+00	OK	1	0	**P6**=P4
0	0.000E+00	0.000E+00	OK	1	0	**h6**=h4
0	0.000E+00	0.000E+00	OK	1	0	**s6**=s4
0	0.000E+00	0.000E+00	OK	1	0	**T6**=T4
0	0.000E+00	0.000E+00	OK	1	0	**x6**=x4
0	0.000E+00	0.000E+00	OK	1	0	**P7**=P6
0	0.000E+00	0.000E+00	OK	1	0	**T7**=T6+DeltaT_reheat
0	0.000E+00	0.000E+00	OK	1	0	**h7**=Enthalpy(Steam,P=P7,T=T7)
0	0.000E+00	0.000E+00	OK	1	0	**s7**=Entropy(Steam,P=P7,h=h7)
0	0.000E+00	0.000E+00	OK	1	0	**T_source_reheat**=(T6+T7)/2
0	0.000E+00	0.000E+00	OK	1	0	**h8s**=Enthalpy(Steam,P=P8,s=s7)
0	0.000E+00	0.000E+00	OK	1	0	**w_LP1**=eta_LP1*(h7-h8s)
0	0.000E+00	0.000E+00	OK	1	0	**h8**=h7-w_LP1
0	0.000E+00	0.000E+00	OK	1	0	**T8**=Temperature(Steam,P=P8,h=h8)
0	0.000E+00	0.000E+00	OK	1	0	**s8**=Entropy(Steam,P=P8,h=h8)
0	0.000E+00	0.000E+00	OK	1	0	**x8**=Quality(Steam,P=P8,h=h8)
0	0.000E+00	0.000E+00	OK	1	0	**P10**=P_cond
0	0.000E+00	0.000E+00	OK	1	0	**h10s**=Enthalpy(Steam,P=P10,s=s8)
0	0.000E+00	0.000E+00	OK	1	0	**w_LP2**=eta_LP2*(h8-h10s)
0	0.000E+00	0.000E+00	OK	1	0	**h10**=h8-w_LP2
0	0.000E+00	0.000E+00	OK	1	0	**T10**=Temperature(Steam,P=P10,h=h10)
0	0.000E+00	0.000E+00	OK	1	0	**s10**=Entropy(Steam,P=P10,h=h10)
0	0.000E+00	0.000E+00	OK	1	0	**x10**=Quality(Steam,P=P10,h=h10)
0	0.000E+00	0.000E+00	OK	1	0	**m_dot_steam**=Q_reactor/(h3-h1)
0	0.000E+00	0.000E+00	OK	1	0	**Q_core**=m_dot_steam*(h3-h1)
0	0.000E+00	0.000E+00	OK	1	0	**Q_reheat**=m_dot_steam*(h7-h6)

0	0.000E+00	0.000E+00	OK	1	0	**Q_in_total**=Q_core+Q_reheat
0	0.000E+00	0.000E+00	OK	1	0	**w_turbine_total**=w_HP+w_LP1+w_LP2
0	0.000E+00	0.000E+00	OK	1	0	**w_net**=w_turbine_total-w_pump
0	0.000E+00	0.000E+00	OK	1	0	**W_turbine_gross**=m_dot_steam*w_turbine_total
0	0.000E+00	0.000E+00	OK	1	0	**W_pump_consumed**=m_dot_steam*w_pump
0	0.000E+00	0.000E+00	OK	1	0	**W_net_mech**=m_dot_steam*w_net
0	0.000E+00	0.000E+00	OK	1	0	**W_elec_gross**=eta_gen*W_net_mech
0	0.000E+00	0.000E+00	OK	1	0	**W_elec_net**=W_elec_gross-W_elec_consume_given
0	0.000E+00	0.000E+00	OK	1	0	**Q_condenser**=m_dot_steam*(h10-h12)
0	0.000E+00	0.000E+00	OK	1	0	**eta_thermal**=W_net_mech/Q_in_total
0	0.000E+00	0.000E+00	?	1	0	**eta_thermal_pct**=100*eta_thermal
0	0.000E+00	0.000E+00	OK	1	0	**eta_plant_net**=W_elec_net/Q_in_total
0	0.000E+00	0.000E+00	OK	1	0	**eta_plant_net_pct**=100*eta_plant_net
0	0.000E+00	0.000E+00	OK	1	0	**W_check**=Q_in_total-Q_condenser
0	0.000E+00	0.000E+00	?	1	0	**FirstLaw_residual**=W_net_mech-W_check
0	0.000E+00	0.000E+00	OK	1	0	**h0**=Enthalpy(Water,T=T0,P=P0)
0	0.000E+00	0.000E+00	OK	1	0	**s0**=Entropy(Water,T=T0,P=P0)
0	0.000E+00	0.000E+00	OK	1	0	**ex1**=(h1-h0)-T0*(s1-s0)
0	0.000E+00	0.000E+00	OK	1	0	**ex3**=(h3-h0)-T0*(s3-s0)
0	0.000E+00	0.000E+00	OK	1	0	**ex4**=(h4-h0)-T0*(s4-s0)
0	0.000E+00	0.000E+00	OK	1	0	**ex6**=(h6-h0)-T0*(s6-s0)
0	0.000E+00	0.000E+00	OK	1	0	**ex7**=(h7-h0)-T0*(s7-s0)
0	0.000E+00	0.000E+00	OK	1	0	**ex8**=(h8-h0)-T0*(s8-s0)
0	0.000E+00	0.000E+00	OK	1	0	**ex10**=(h10-h0)-T0*(s10-s0)
0	0.000E+00	0.000E+00	OK	1	0	**ex12**=(h12-h0)-T0*(s12-s0)
0	0.000E+00	0.000E+00	OK	1	0	**Ex_1**=m_dot_steam*ex1
0	0.000E+00	0.000E+00	OK	1	0	**Ex_3**=m_dot_steam*ex3
0	0.000E+00	0.000E+00	OK	1	0	**Ex_4**=m_dot_steam*ex4
0	0.000E+00	0.000E+00	OK	1	0	**Ex_6**=m_dot_steam*ex6
0	0.000E+00	0.000E+00	OK	1	0	**Ex_7**=m_dot_steam*ex7
0	0.000E+00	0.000E+00	OK	1	0	**Ex_8**=m_dot_steam*ex8
0	0.000E+00	0.000E+00	OK	1	0	**Ex_10**=m_dot_steam*ex10
0	0.000E+00	0.000E+00	OK	1	0	**Ex_12**=m_dot_steam*ex12
0	0.000E+00	0.000E+00	OK	1	0	**W_HP_mech**=m_dot_steam*w_HP
0	0.000E+00	0.000E+00	OK	1	0	**W_LP1_mech**=m_dot_steam*w_LP1
0	0.000E+00	0.000E+00	OK	1	0	**W_LP2_mech**=m_dot_steam*w_LP2
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_HP**=Ex_3-Ex_4-W_HP_mech
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_LP1**=Ex_7-Ex_8-W_LP1_mech
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_LP2**=Ex_8-Ex_10-W_LP2_mech
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_pump**=Ex_12+W_pump_consumed-Ex_1
0	0.000E+00	0.000E+00	OK	1	0	**T_cond_avg**=(T10+T12)/2
0	0.000E+00	0.000E+00	OK	1	0	**Ex_loss_cond**=Q_condenser*(1-T0/T_cond_avg)
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_cond**=Ex_10-Ex_12-Ex_loss_cond
0	0.000E+00	0.000E+00	OK	1	0	**Ex_in_reactor**=Q_reactor*(1-T0/T3)
0	0.000E+00	0.000E+00	OK	1	0	**Ex_in_reheat**=Q_reheat*(1-T0/T_source_reheat)
0	0.000E+00	0.000E+00	OK	1	0	**Ex_in_total**=Ex_in_reactor+Ex_in_reheat
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_reactor**=Ex_in_reactor-(Ex_3-Ex_1)
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_reheat**=Ex_in_reheat-(Ex_7-Ex_6)
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_gen**=W_net_mech*(1-eta_gen)
0	0.000E+00	0.000E+00	OK	1	0	**Ex_loss_house**=W_elec_consume_given
0	0.000E+00	0.000E+00	OK	1	0	**Ex_total_losses**=Ex_dest_HP+Ex_dest_LP1+Ex_dest_LP2+Ex_dest_pum
0	0.000E+00	0.000E+00	OK	1	0	**eta_exergy**=W_elec_net/Ex_in_total
0	0.000E+00	0.000E+00	?	1	0	**eta_exergy_pct**=100*eta_exergy
0	0.000E+00	0.000E+00	OK	1	0	**Ex_balance**=Ex_in_total-(W_elec_net+Ex_total_losses)
0	0.000E+00	0.000E+00	OK	1	0	**T_cw_out**=T_cw_in+DeltaT_cw
0	0.000E+00	0.000E+00	OK	1	0	**T_cw_avg**=(T_cw_in+T_cw_out)/2

0	0.000E+00	0.000E+00	OK	1	0	**cp_cw**=Cp(Water,T=T_cw_avg,P=P0)
0	0.000E+00	0.000E+00	OK	1	0	**v_cw**=Volume(Water,T=T_cw_avg,P=P0)
0	0.000E+00	0.000E+00	OK	1	0	**m_dot_cw**=Q_condenser/(cp_cw*DeltaT_cw)
0	0.000E+00	0.000E+00	OK	1	0	**V_dot_cw**=m_dot_cw*v_cw
0	0.000E+00	0.000E+00	OK	1	0	**eta_th_core_only**=W_net_mech/Q_core
0	0.000E+00	0.000E+00	?	1	0	**eta_th_core_only_pct**=100*eta_th_core_only
0	0.000E+00	0.000E+00	OK	1	0	**eta_th_total**=W_net_mech/Q_in_total
0	0.000E+00	0.000E+00	?	1	0	**eta_th_total_pct**=100*eta_th_total
0	0.000E+00	0.000E+00	OK	1	0	**eta_plant_net_core**=W_elec_net/Q_core
0	0.000E+00	0.000E+00	?	1	0	**eta_plant_net_core_pct**=100*eta_plant_net_core
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_reactor_bucket**=Ex_dest_reactor
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_reheat_bucket**=Ex_dest_reheat
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_HP_bucket**=Ex_dest_HP
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_LP1_bucket**=Ex_dest_LP1
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_LP2_bucket**=Ex_dest_LP2
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_pump_bucket**=Ex_dest_pump
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_cond_bucket**=Ex_dest_cond
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_gen_bucket**=Ex_dest_gen
0	0.000E+00	0.000E+00	OK	1	0	**Ex_dest_house_bucket**=Ex_loss_house
0	0.000E+00	0.000E+00	OK	1	0	**Ex_loss_to_cooling**=Ex_loss_cond
0	0.000E+00	0.000E+00	OK	1	0	**Ex_total_losses_check**=Ex_dest_reactor_bucket+Ex_dest_reheat_bucke
0	0.000E+00	0.000E+00	OK	1	0	**Ex_balance_summary**=Ex_in_total-(W_elec_net+Ex_total_losses_check)
0	0.000E+00	0.000E+00	OK	1	0	**house_load_fraction_elec**=W_elec_consume_given/W_elec_gross
0	0.000E+00	0.000E+00	?	1	0	**house_load_fraction_elec_pct**=100*house_load_fraction_elec
0	0.000E+00	0.000E+00	OK	1	0	**P[1]**=P1
0	0.000E+00	0.000E+00	OK	1	0	**P[3]**=P3
0	0.000E+00	0.000E+00	OK	1	0	**P[4]**=P4
0	0.000E+00	0.000E+00	OK	1	0	**P[6]**=P6
0	0.000E+00	0.000E+00	OK	1	0	**P[7]**=P7
0	0.000E+00	0.000E+00	OK	1	0	**P[8]**=P8
0	0.000E+00	0.000E+00	OK	1	0	**P[10]**=P10
0	0.000E+00	0.000E+00	OK	1	0	**P[12]**=P12
0	0.000E+00	0.000E+00	OK	1	0	**T[1]**=T1
0	0.000E+00	0.000E+00	OK	1	0	**T[3]**=T3
0	0.000E+00	0.000E+00	OK	1	0	**T[4]**=T4
0	0.000E+00	0.000E+00	OK	1	0	**T[6]**=T6
0	0.000E+00	0.000E+00	OK	1	0	**T[7]**=T7
0	0.000E+00	0.000E+00	OK	1	0	**T[8]**=T8
0	0.000E+00	0.000E+00	OK	1	0	**T[10]**=T10
0	0.000E+00	0.000E+00	OK	1	0	**T[12]**=T12
0	0.000E+00	0.000E+00	OK	1	0	**h[1]**=h1
0	0.000E+00	0.000E+00	OK	1	0	**h[3]**=h3
0	0.000E+00	0.000E+00	OK	1	0	**h[4]**=h4
0	0.000E+00	0.000E+00	OK	1	0	**h[6]**=h6
0	0.000E+00	0.000E+00	OK	1	0	**h[7]**=h7
0	0.000E+00	0.000E+00	OK	1	0	**h[8]**=h8
0	0.000E+00	0.000E+00	OK	1	0	**h[10]**=h10
0	0.000E+00	0.000E+00	OK	1	0	**h[12]**=h12
0	0.000E+00	0.000E+00	OK	1	0	**s[1]**=s1
0	0.000E+00	0.000E+00	OK	1	0	**s[3]**=s3
0	0.000E+00	0.000E+00	OK	1	0	**s[4]**=s4
0	0.000E+00	0.000E+00	OK	1	0	**s[6]**=s6
0	0.000E+00	0.000E+00	OK	1	0	**s[7]**=s7
0	0.000E+00	0.000E+00	OK	1	0	**s[8]**=s8
0	0.000E+00	0.000E+00	OK	1	0	**s[10]**=s10
0	0.000E+00	0.000E+00	OK	1	0	**s[12]**=s12

0	0.000E+00	0.000E+00	OK	1	0	**x[4]**=x4
0	0.000E+00	0.000E+00	OK	1	0	**x[6]**=x6
0	0.000E+00	0.000E+00	OK	1	0	**x[8]**=x8
0	0.000E+00	0.000E+00	OK	1	0	**x[10]**=x10
0	0.000E+00	0.000E+00	OK	1	0	**x[12]**=x12
0	0.000E+00	0.000E+00	OK	1	0	**ex[1]**=ex1
0	0.000E+00	0.000E+00	OK	1	0	**ex[3]**=ex3
0	0.000E+00	0.000E+00	OK	1	0	**ex[4]**=ex4
0	0.000E+00	0.000E+00	OK	1	0	**ex[6]**=ex6
0	0.000E+00	0.000E+00	OK	1	0	**ex[7]**=ex7
0	0.000E+00	0.000E+00	OK	1	0	**ex[8]**=ex8
0	0.000E+00	0.000E+00	OK	1	0	**ex[10]**=ex10
0	0.000E+00	0.000E+00	OK	1	0	**ex[12]**=ex12

Parametric Table: Condenser Pressure

	Pcond	$W_{elec,net}$	$Ex_{dest,cond}$	$Ex_{loss,cond}$	$\eta_{plant,net,pct}$
Run 1	5	301748	-0.01986	16966	30.62
Run 2	6	297523	0.4213	23836	30.17
Run 3	7	293867	0.7642	29745	29.78
Run 4	8	290636	1.032	34939	29.44
Run 5	9	287736	1.242	39583	29.14
Run 6	10	285100	1.408	43786	28.86
Run 7	11	282681	1.538	47629	28.6
Run 8	12	280443	1.639	51173	28.37
Run 9	13	278358	1.718	54464	28.15
Run 10	14	276406	1.779	57537	27.94

Parametric Table: T Core Outlet

	TcoreOut	$\dot{m}_{steam}$	$W_{elec,net}$	$\eta_{thermal,pct}$	$\eta_{plant,net,pct}$	$\eta_{exergy,pct}$
Run 1	545	851.3	622036	28.51	26.65	63.68
Run 2	550	830.3	608341	28.58	26.7	63.42
Run 3	555	810	595219	28.67	26.75	63.17
Run 4	560	790.3	582618	28.75	26.8	62.92
Run 5	565	332.1	292191	33.56	29.82	64.25
Run 6	570	329.1	290336	33.63	29.87	63.71
Run 7	575	326.3	288685	33.71	29.92	63.19
Run 8	580	323.8	287198	33.78	29.97	62.69
Run 9	585	321.4	285847	33.85	30.02	62.21
Run 10	590	319.1	284610	33.92	30.07	61.74

Parametric Table: T Difference Reheat

	Treheat	x8	x10	$W_{elec,net}$	$\eta_{plant,net,pct}$	$Ex_{dest,LP1}$	$Ex_{dest,LP2}$	$Ex_{dest,reheat}$
Run 1	1	0.8966	0.7884	283738	29.68	8483	15229	55.1
Run 2	10	0.9067	0.7958	286490	29.7	8594	15385	550
Run 3	20	0.9171	0.8033	289461	29.73	8720	15545	1094
Run 4	25	0.922	0.8069	290932	29.74	8785	15621	1364
Run 5	30	0.9268	0.8104	292400	29.76	8851	15695	1634
Run 6	35	0.9315	0.8138	293867	29.78	8919	15767	1902
Run 7	40	0.9361	0.8171	295334	29.81	8988	15837	2170
Run 8	50	0.9449	0.8235	298277	29.86	9130	15973	2705