Performance Evaluation of Evaporator vs Reverse Osmosis System for Producing Condensate Quality Water

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ABSTRACT

American Electric Power is currently in the process of evaluating the benefits of replacing the evaporators with a reverse osmosis system for producing condensate quality water at one of its plant sites. Advantages of the reverse osmosis system include improvements in cycle efficiency and improved water quality. PEPSE heat balance models were used to evaluate the changes in cycle efficiency for removing the evaporators from service. This paper discusses the results of the PEPSE studies as well as some of the technical benefits of the reverse osmosis system.

INTRODUCTION

The plant site consists of five generating units ranging in size from 205 MWN to 585 MWN. The first four units are subcritical units with single reheat, while Unit 5 is a supercritical unit with double reheat. Units 1 and 2 are identical, and 3 and 4 are also identical. All five units currently use an evaporator system for producing condensate quality water used for makeup of water losses in the steam cycle. Unit 5 also employs a condensate cleanup system to ensure its water is of an exceptionally high quality required for supercritical units.

The evaporators produce purified water by distillation (the process of evaporating and condensing a liquid). Extraction steam is used to evaporate the water which is then condensed in the evaporator condenser (or in the deaerator for Units 1-4). Impurities left behind in the evaporator are removed by continuous blowdown. Cycle inefficiencies and some carry-over of impurities are inherent with all evaporator systems.

As a means of improving cycle efficiency and water quality, AEP is considering replacing the evaporators on all five units with a single reverse osmosis (RO) system to provide the purified water required for makeup.

The reverse osmosis system is essentially a membrane filter capable of removing dissolved solids from pretreated water. The RO membrane is designed to have a porosity which limits the passage of larger ions but allows the smaller water molecules to pass through. Pretreated water is diffused through the membrane by application of higher hydraulic pressure on one side of the membrane to effect flow. The concentrated brine containing the filtered impurities is routed to waste. The membrane surfaces must be chemically cleaned every 3 to 12 months depending on the incoming water quality and ultimately must be replaced every three to five years. The reverse osmosis system requires additional pumping power that is not required by the evaporator system.

The primary advantages of the reverse osmosis system are the improvements in cycle efficiency and the improved water quality delivered by the system. The improved water quality reduces scaling on the inside of boiler tube surfaces which prevents overheating and increases boiler tube life. Also, the reverse osmosis system is capable of producing purified water when the plant is shut down.

The following section discusses the heat balance study conducted using PEPSE to evaluate the performance improvements expected by replacing the evaporators with a reverse osmosis system. The results of this study will be used to evaluate the economic benefits of improved heat rate and extra generation capacity against the cost of installing the reverse osmosis system. The operating and maintenance costs of both systems will also be considered in AEP's economic evaluation.

HEAT BALANCE STUDY

PEPSE heat balance models, developed in the late 1980's and recently converted to PC, were used to evaluate the effect of heat rate for removing the evaporators from service. Heat balance drawings, recently developed using PEPSE, were used to present results.

The heat balance study was conducted by comparing the base case heat balance (evaporators in service) at full load to a case run with the evaporators removed from service for each unit series. Changes in auxiliary power due to the additional pumping power required by the reverse osmosis system were not considered in these heat balance studies. Instead the impact due to aux power is considered on the total plant basis discussed later in this report. The following is a description of the heat balance study conducted for each unit series and a summary of the changes noted in cycle performance.

Units 1 and 2

The evaporators on Units 1 and 2 are designed to evaporate up to 27,000 PPH water using steam from the 4th stage extraction of the IP Turbine. A continuous blowdown of 10% from the evaporator is required to remove impurities. The base case heat balance uses the full load evaporation rate of 20,000 PPH, which requires a makeup water supply of 22,222 PPH with 10% evaporator blowdown. The makeup vapor flows to the deaerator where it is condensed. A boiler blowdown rate of 3,000 PPH is included in the base case heat balance which is required to remove impurities carried over from the evaporator and picked up elsewhere in the cycle.

With the evaporator removed from service, the heat balance includes makeup water (treated by the reverse osmosis system) introduced to the cycle at the condenser hotwell. Due to the improved quality of water, boiler blowdown is assumed to be reduced by 50% (this is typical of the improvements noted at other AEP subcritical plants that have recently installed reverse osmosis systems). With the reduction of boiler blowdown and elimination of the evaporator blowdown, only 18,500 PPH makeup water is required (to replace steam losses, water losses, and boiler blowdown). The heat balances for the base case (evaporator in service) and with the evaporator removed from service are presented as Figures 1 and 2.

Without considering the increase in aux power, Net Unit Heat Rate (NUHR) is reduced by 22.7 Btu/kwh and generation is increased by 443 KW with the evaporator removed from service. A summary of the changes in cycle performance for Units 1 and 2 is presented in the following table.

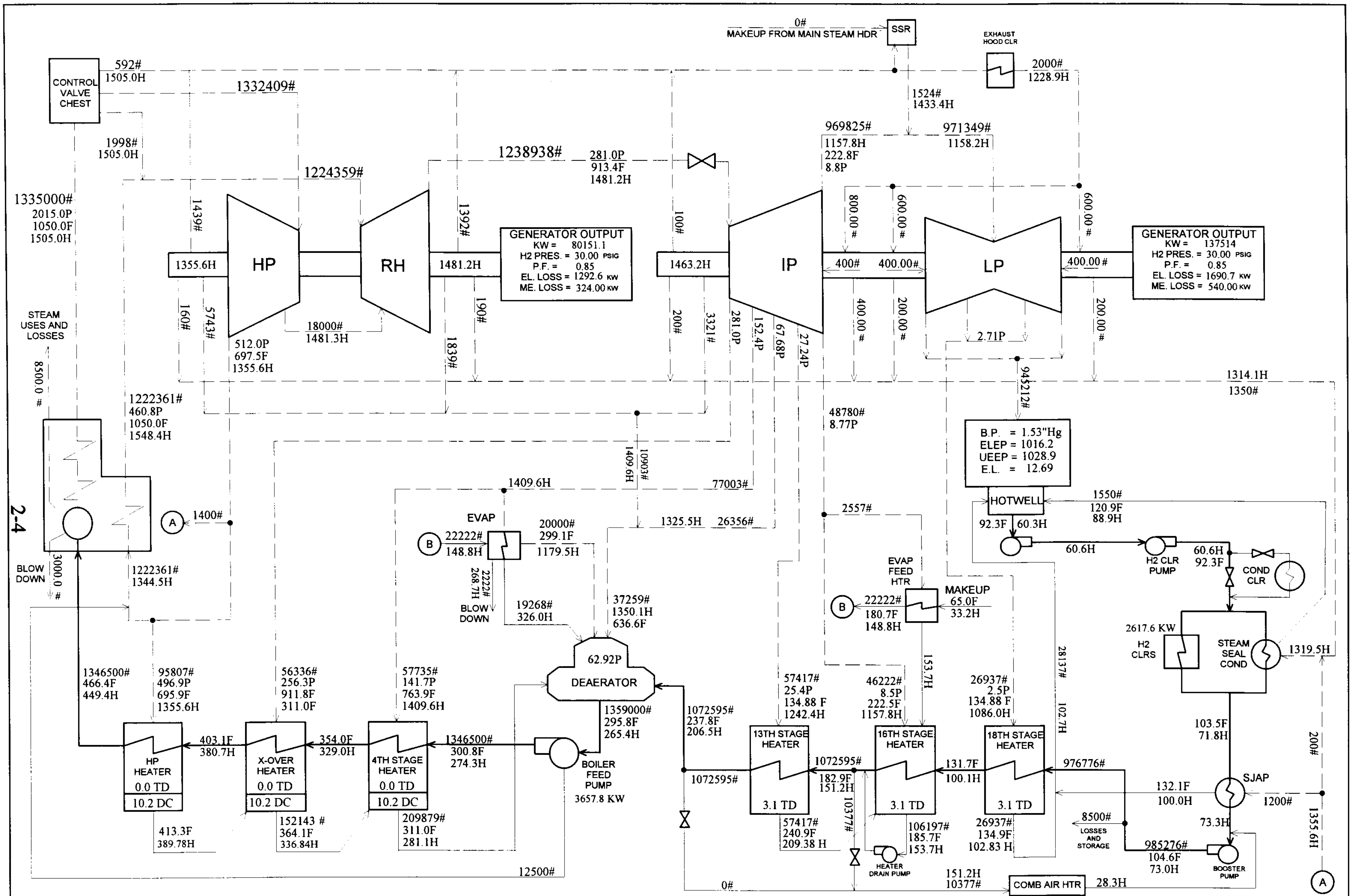
Units 1 and 2 - Change in Cycle Performance

	Evaporator I/S	Evaporator O/S	Change
Makeup Water, PPH	22,222	18,500	-3,722
Evaporator Blowdown, PPH	2,222	0	-2,222
Boiler Blowdown, PPH	3,000	1,500	-1,500
NUHR, Btu/kwh	9349.4	9326.7	-22.7
Net Generation, KW	201,470	201,913	443

The improvement in cycle efficiency is due to a combination of: (1) thermodynamic benefits due to improved utilization of extraction steam, (2) reduction in boiler blowdown losses, (3) elimination of evaporator blowdown losses, and (4) a shift in turbine available energy.

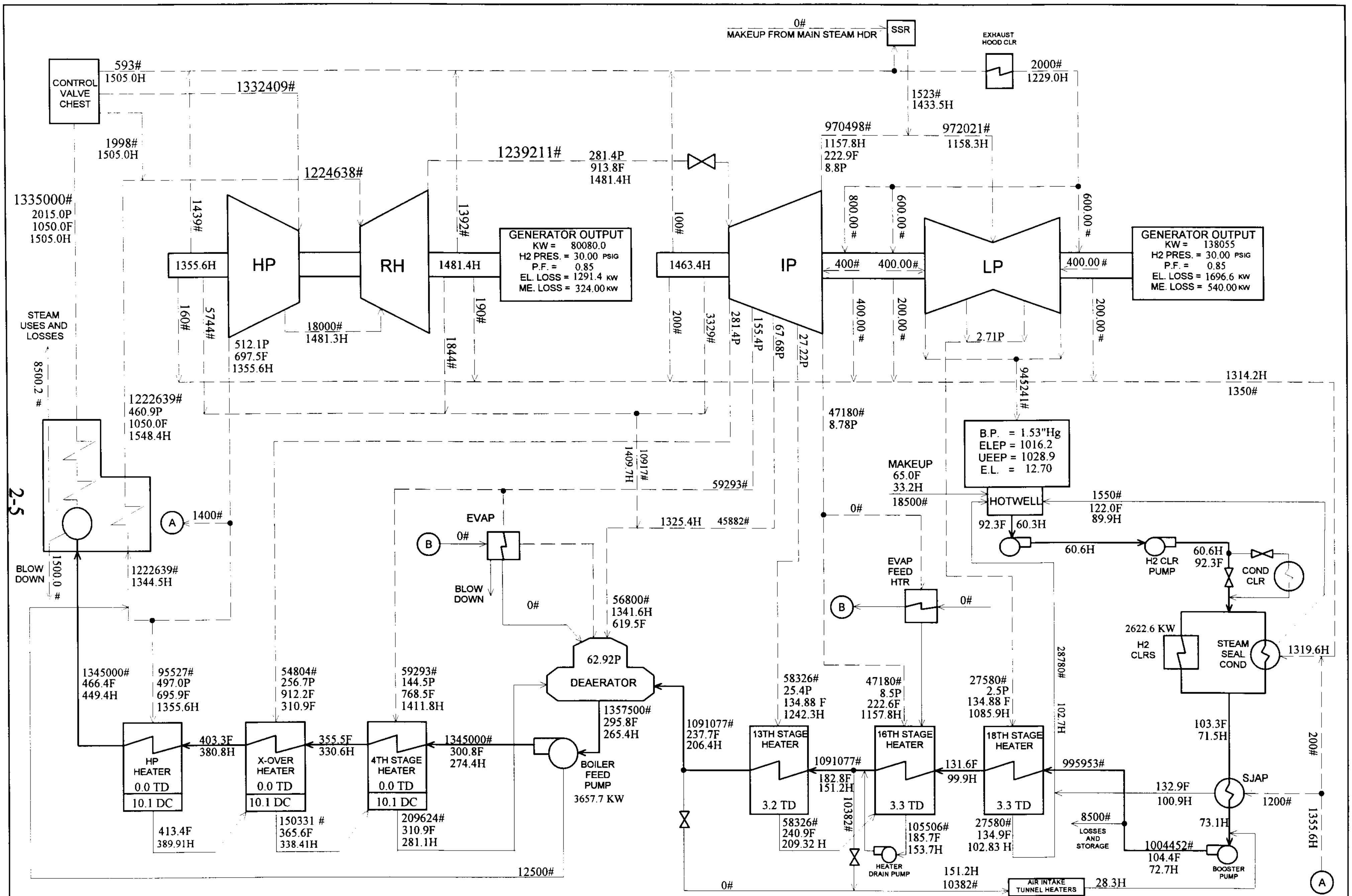
The primary gain in cycle efficiency is due to the thermodynamic improvements in use of extraction steam. With the evaporator in-service, heat taken from the 4th stage extraction is used to replace heat which would have been provided by the 9th stage extraction (to deaerator); i.e., steam used to supply the evaporator (enthalpy of 1409.6 Btu/lb) replaces steam which would have been extracted from the next lower extraction (enthalpy of 1325.5 Btu/lb), and thus bypasses a number of turbine stages resulting in lower turbine output.

The change in extraction steam flow also causes a shift in turbine stage pressures which results in a change in available energy to the turbines. With the evaporator removed from service, the IP Turbine operates at a higher inlet pressure. This results in an increased output from the more efficient IP/LP Turbine which is somewhat offset by the lower output from the HP/RH Turbine. This effect is minor compared to the thermodynamic improvements in utilization of extraction steam.



SYMBOLS	TURBINE EFFICIENCIES			AMERICAN ELECTRIC POWER
# - LB\HR P - PSIA F - DEGREE F H - BTU/LB	HP = 82.70 RH = 87.62 LP = 89.47	% THROTTLE FLOW = 100.00 GROSS GEN (KW) = 217666 NET GEN (KW) = 201470 AUX POWER (KW) = 16196.0 Evaporator i/s	GTHR (BTU/KWH) = 7648.7 NUHR (BTU/KWH) = 9349.4 BOILER EFF (%) = 88.39 C W TEMP (F) = 65.0F	UNITS 1 AND 2 PEPSE RUN: 04/09/97 DRAWING DATE: 3/24/97

Figure 1



SYMBOLS	TURBINE EFFICIENCIES			AMERICAN ELECTRIC POWER
# - LB\HR P - PSIA F - DEGREE F H - BTU/LB	HP = 82.70 RH = 87.61 LP = 89.47	% THROTTLE FLOW = 100.00 GROSS GEN (KW) = 218135 NET GEN (KW) = 201913 AUX POWER (KW) = 16223.1 Evaporator o/s	GTHR (BTU/KWH) = 7630.5 NUHR (BTU/KWH) = 9326.7 BOILER EFF (%) = 88.39 C W TEMP (F) = 65.0F	UNITS 1 AND 2 PEPSE RUN: 03/24/97 DRAWING DATE: 3/24/97

Figure 2

Of the total improvement in cycle efficiency, approximately 78% is due to thermodynamic improvements in steam utilization and the shift in turbine work, 17% is due to reduction of boiler blowdown, and 5% is due to elimination of the evaporator blowdown.

Units 3 and 4

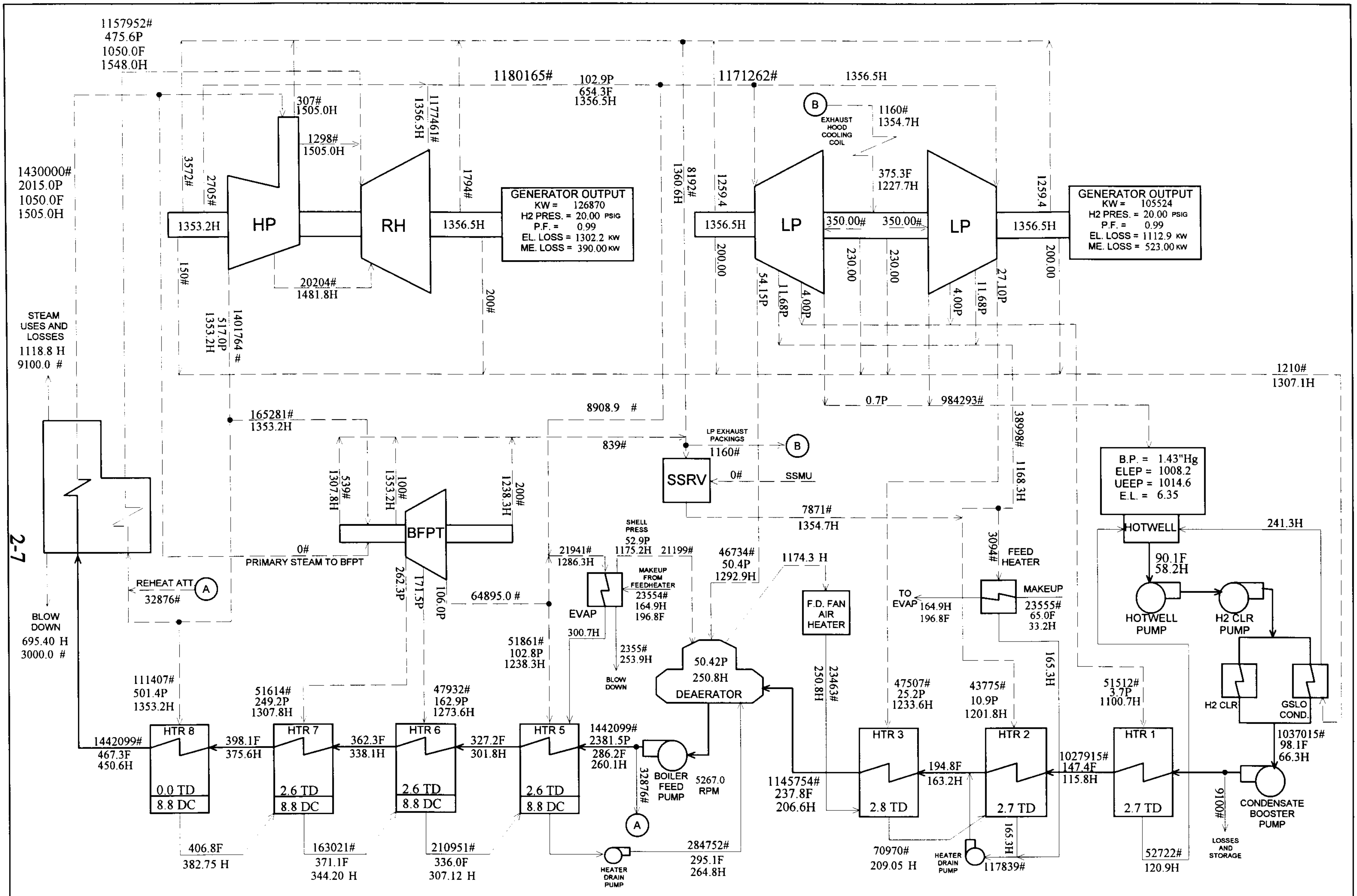
The evaporator on Units 3 and 4 is designed to evaporate up to 30,000 PPH water using a mix of steam from the RH Turbine and BFP Turbine exhausts. The base case heat balance used the full load evaporation rate of 21,200 PPH, which results in a total makeup water flow rate of 23,554 PPH with 10% evaporator blowdown. The makeup vapor enters the deaerator where it is condensed. A boiler blowdown rate of 3,000 PPH is included in the base case heat balance.

With the evaporator removed from service, the heat balance includes makeup water (treated by the reverse osmosis system) introduced to the cycle downstream of the condenser hotwell. Boiler blowdown is assumed to be reduced by 50% (due to the higher quality water produced by the reverse osmosis system). With the reduction of boiler blowdown and elimination of the evaporator blowdown, only 19,700 PPH makeup water is required. The heat balances for the base case (evaporator in service) and with the evaporator removed from service are presented as Figures 3 and 4.

Net Unit Heat Rate (NUHR) is reduced by 5.8 Btu/kwh and generation is increased by 105 KW by removing the evaporator from service. A summary of the changes in cycle performance for Units 3 and 4 is presented below.

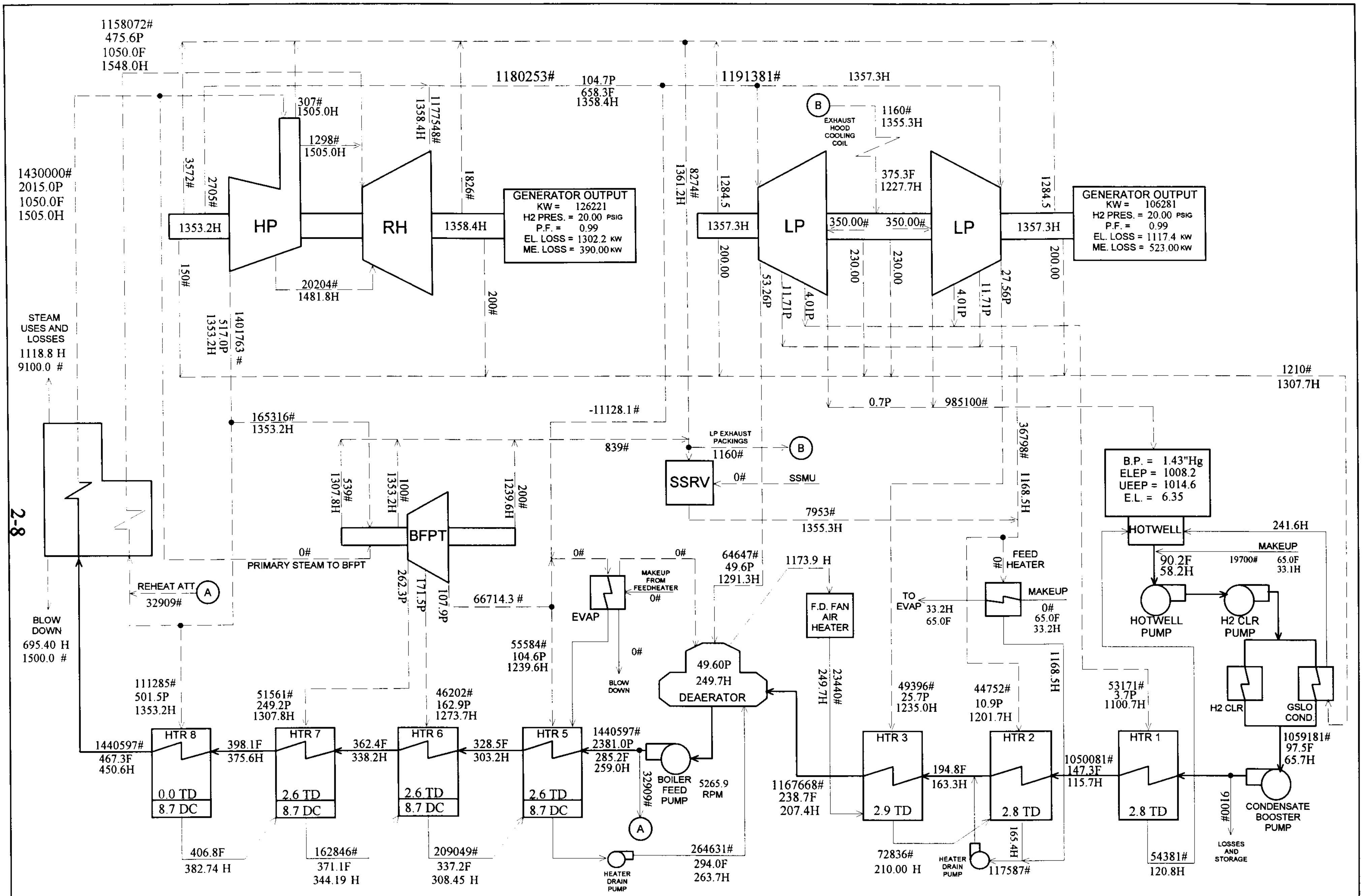
Units 3 and 4 - Change in Cycle Performance			
	Evaporator I/S	Evaporator O/S	Change
Makeup Water, PPH	23,554	19,700	-3,855
Evaporator Blowdown, PPH	2,355	0	-2,355
Boiler Blowdown, PPH	3,000	1,500	-1,500
NUHR, Btu/kwh	8971.6	8965.8	-5.8
Net Generation, KW	223,355	223,460	105

For Units 3 and 4 there is minimal loss of thermodynamic availability due to use of extraction steam for evaporation. In the base case, the extraction steam from the RHT and BFPT exhausts has a combined enthalpy of 1286.3 Btu/lb which replaces extraction steam provided from the LPT extraction to the deaerator (enthalpy of 1292.9 Btu/lb). The use of the BFPT exhaust steam, with relatively low energy but suitable pressure required for evaporation of the makeup water, is more efficient than the use of steam from the next higher extraction as in the cycle for Units 1 and 2.



SYMBOLS	TURBINE EFFICIENCIES				AMERICAN ELECTRIC POWER
# - LB\HR P - PSIA F - DEGREE F H - BTU/LB	HPT = 84.52 RHT = 89.72 LPT = 89.76	FEED PUMP TURB = 72.43 FEED PUMP = 79.61	% THROTTLE FLOW = 100.00 GROSS GEN (KW) = 232394 NET GEN (KW) = 223355 AUX POWER (KW) = 9039.4 Evaporator i/s	GTHR (BTU/KWH) = 7642.7 NUHR (BTU/KWH) = 8971.6 BOILER EFF (%) = 88.64 C W TEMP (F) = 65.0F	UNITS 3 AND 4 PEPSE RUN: 03/24/97 DRAWING DATE: 4/25/97

Figure 3



SYMBOLS
\# - LB\HR
P - PSIA
F - DEGREE F
H - BTU/LB

TURBINE EFFICIENCIES

HPT = 84.52
RHT = 89.70
LPT = 89.62

FEED PUMP TURB = 72.29

FEED PUMP = 79.60

% THROTTLE FLOW = 100.00
GROSS GEN (KW) = 232502
NET GEN (KW) = 223460
AUX POWER (KW) = 9042.0

Evaporator o/s

GTHR (BTU/KWH) = 7637.8
NUHR (BTU/KWH) = 8965.8
BOILER EFF (%) = 88.64
C W TEMP (F) = 65.0F

AMERICAN ELECTRIC POWER

UNITS 3 AND 4

PEPSE RUN: 03/24/97

DRAWING DATE: 2/04/97

Figure 4

The changes in extraction steam result a shift in turbine available energy due to an increase in RHT exhaust pressure with the evaporator removed from service. This results in an increased LPT output which is offset by a reduced output from the RHT. On these units, the shift in turbine available energy has little effect on cycle efficiency since both the RHT and LPT have nearly identical efficiencies.

The improvement in cycle efficiency with evaporator removed from service is due primarily to the reduction of boiler blowdown (62%) and elimination of the evaporator blowdown (19%) with the remaining due to thermodynamic improvements of the cycle.

Unit 5

The evaporator on Unit 5 is designed to evaporate up to 50,000 PPH water using steam from the 2nd RH Turbine exhaust. The heat balance study was conducted using the full load evaporation rate of 28,800 PPH, which results in a total pretreated water requirement of 32,000 PPH with 10% evaporator blowdown. The vapor is condensed in the evaporator condenser. From the evaporator condenser the condensed water flows to the feed heater and then to the condensate storage tank. In order to ensure that the water is of an exceptionally high purity required for supercritical units, the water is further treated by the condensate cleanup system before being introduced into the cycle for makeup. The heat balance for Unit 5 base case (evaporator in-service) is presented as Figure 5.

To evaluate the evaporator removed from service, the pretreated water to the evaporator was set to zero (see Figure 6). In this case, the pretreated water is purified by the reverse osmosis system and then sent to storage. For the Unit 5 heat balance studies, makeup water entering the cycle was not modeled.

Net Unit Heat Rate (NUHR) is reduced by 3.2 Btu/kwh and generation is increased by 212 KW by removing the evaporator from service. A summary of the changes in cycle performance for Unit 5 is presented below.

Unit 5 - Change in Cycle Performance			
	Evaporator I/S	Evaporator O/S	Change
Water to Evaporator, PPH	32,000	0	n/a
Evaporator Blowdown, PPH	3,200	0	-3,200
Water to Storage, PPH	28,800	0	n/a
NUHR, Btu/kwh	8712.0	8708.8	-3.2
Net Generation, KW	587,342	587,554	212

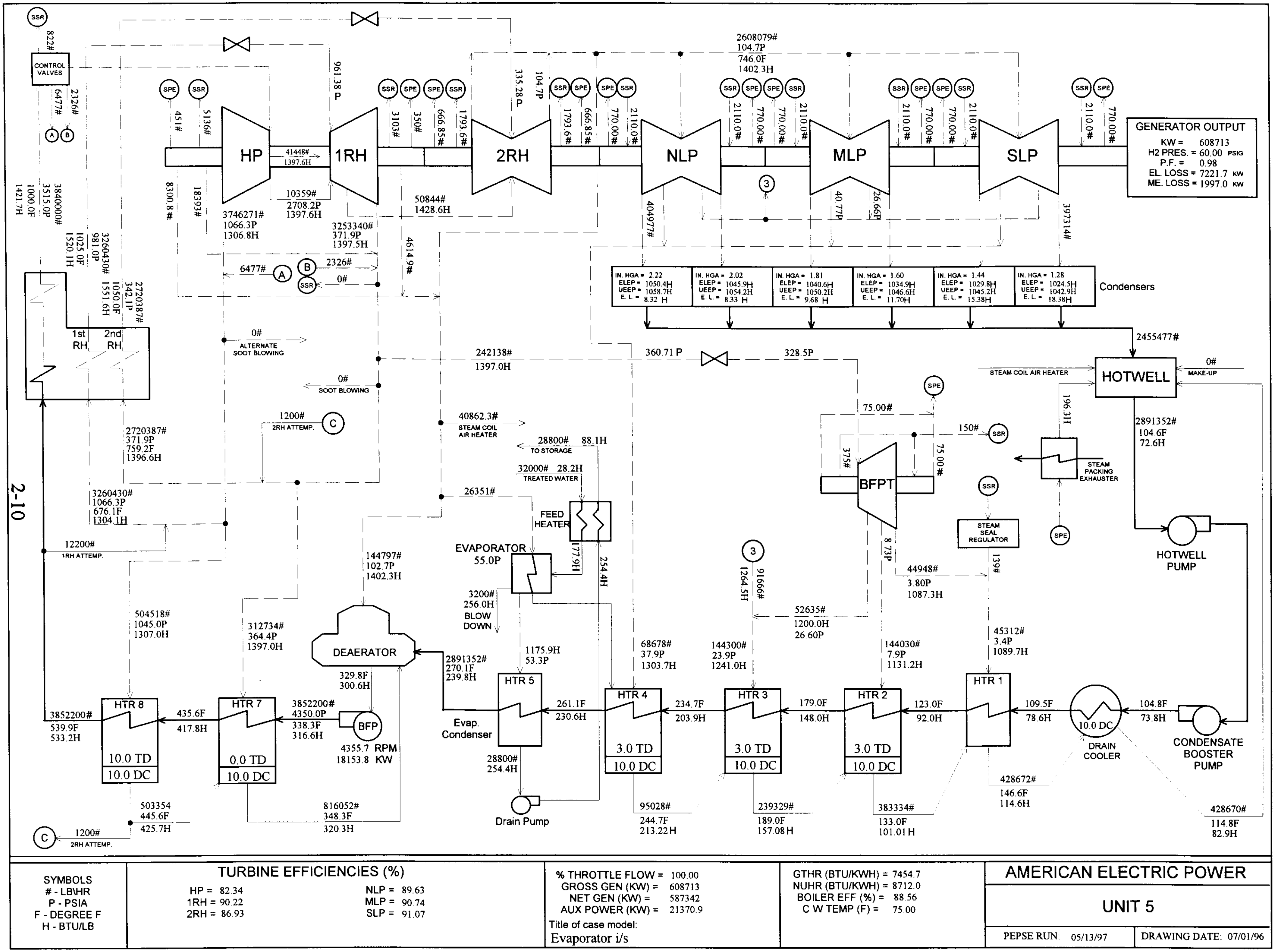
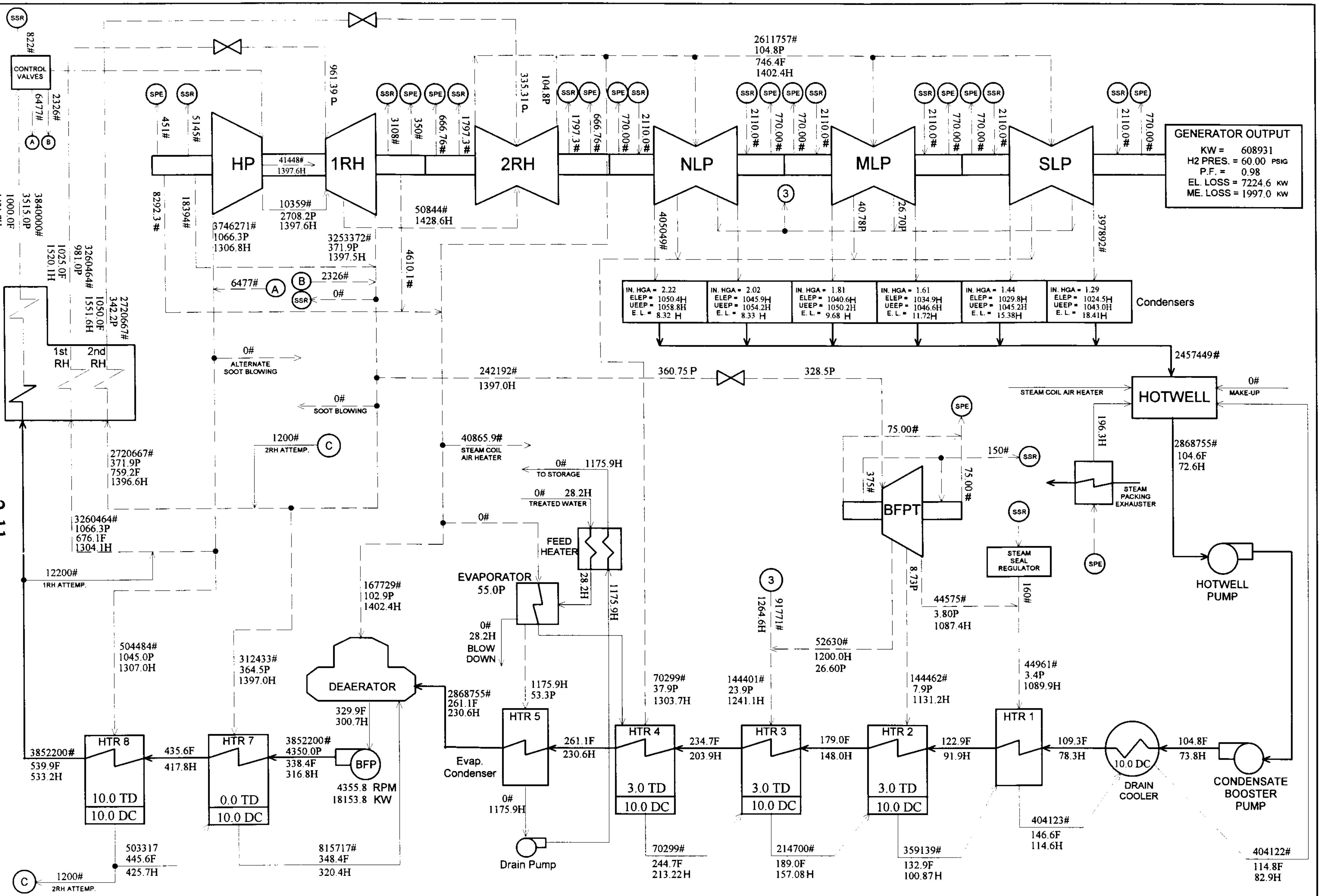

GENERATOR OUTPUT
KW = 608713
H2 PRES. = 60.00 PSIG
P.F. = 0.98
EL. LOSS = 7221.7 KW
ME. LOSS = 1997.0 KW
HP
1RH
2RH
NLP
MLP
SLP
CONTROL VALVES
822#
6477#
2326#
3840000#
3515.0P
1000.0F
1421.7H
451#
5136#
8300.8#
18393#
41448#
1397.6H
10359#
2708.2P
1397.6H
3746271#
1066.3P
1306.8H
961.38 P
3103#
350#
666.85#
1793.6#
335.28 P
104.7P
50844#
1428.6H
3253340#
371.9P
1397.5H
4614.9#
2608079#
104.7P
746.0F
1402.3H
1793.6#
666.85#
770.00#
2110.0#
404977#
40.77P
26.66P
397314#
IN. HGA = 2.22 ELEP = 1050.4H UEEP = 1058.7H E.L. = 8.32 H
IN. HGA = 2.02 ELEP = 1045.9H UEEP = 1054.2H E.L. = 8.33 H
IN. HGA = 1.81 ELEP = 1040.6H UEEP = 1050.2H E.L. = 9.68 H
IN. HGA = 1.60 ELEP = 1034.9H UEEP = 1046.6H E.L. = 11.70H
IN. HGA = 1.44 ELEP = 1029.8H UEEP = 1045.2H E.L. = 15.38H
IN. HGA = 1.28 ELEP = 1024.5H UEEP = 1042.9H E.L. = 18.38H
Condensers
2455477#
HOTWELL
STEAM COIL AIR HEATER
0#
MAKE-UP
196.3H
2891352#
104.6F
72.6H
STEAM PACKING EXHAUSTER
HOTWELL PUMP
CONDENSATE BOOSTER PUMP
DRAIN COOLER
10.0 DC
104.8F
73.8H
109.5F
78.6H
428670#
114.8F
82.9H
428672#
146.6F
114.6H
STEAM SEAL REGULATOR
139#
45312#
3.4P
1089.7H
BFPT
75.00#
150#
375#
8.73P
44948#
3.80P
1087.3H
52635#
1200.0H
26.60P
91666#
1264.5H
242138#
1397.0H
360.71 P
328.5P
0#
ALTERNATE SOOT BLOWING
0#
SOOT BLOWING
1200#
2RH ATTEMP.
40862.3#
STEAM COIL AIR HEATER
28800#
88.1H
TO STORAGE
32000#
28.2H
TREATED WATER
26351#
FEED HEATER
177.9H
254.4H
EVAPORATOR
55.0P
3200#
256.0H
BLOW DOWN
144797#
102.7P
1402.3H
DEAERATOR
2891352#
270.1F
239.8H
329.8F
300.6H
BFP
4355.7 RPM
18153.8 KW
3852200#
4350.0P
338.3F
316.6H
816052#
348.3F
320.3H
Evap. Condenser
1175.9H
53.3P
HTR 5
261.1F
230.6H
28800#
254.4H
Drain Pump
68678#
37.9P
1303.7H
HTR 4
3.0 TD
10.0 DC
95028#
244.7F
213.22H
234.7F
203.9H
144300#
23.9P
1241.0H
HTR 3
239329#
189.0F
157.08H
179.0F
148.0H
144030#
7.9P
1131.2H
HTR 2
383334#
133.0F
101.01H
123.0F
92.0H
HTR 1
2720387#
342.1P
1050.0F
1551.6H
3260430#
981.0P
1025.0F
1520.1H
1st RH
2nd RH
2720387#
371.9P
759.2F
1396.6H
3260430#
1066.3P
676.1F
1304.1H
12200#
1RH ATTEMP.
504518#
1045.0P
1307.0H
312734#
364.4P
1397.0H
HTR 8
10.0 TD
10.0 DC
HTR 7
0.0 TD
10.0 DC
435.6F
417.8H
3852200#
539.9F
533.2H
503354
445.6F
425.7H
1200#
2RH ATTEMP.
SYMBOLS
- LB\HR
P - PSIA
F - DEGREE F
H - BTU/LB
TURBINE EFFICIENCIES (%)
HP = 82.34
1RH = 90.22
2RH = 86.93
NLP = 89.63
MLP = 90.74
SLP = 91.07
% THROTTLE FLOW = 100.00
GROSS GEN (KW) = 608713
NET GEN (KW) = 587342
AUX POWER (KW) = 21370.9
Title of case model:
Evaporator i/s
GTHR (BTU/KWH) = 7454.7
NUHR (BTU/KWH) = 8712.0
BOILER EFF (%) = 88.56
C W TEMP (F) = 75.00
AMERICAN ELECTRIC POWER
UNIT 5
PEPSE RUN: 05/13/97
DRAWING DATE: 07/01/96

Figure 5



SYMBOLS	TURBINE EFFICIENCIES (%)			AMERICAN ELECTRIC POWER
# - LB\HR P - PSIA F - DEGREE F H - BTU/LB	HP = 82.34 1RH = 90.22 2RH = 86.93 NLP = 89.63 MLP = 90.74 SLP = 91.07	% THROTTLE FLOW = 100.00 GROSS GEN (KW) = 608931 NET GEN (KW) = 587554 AUX POWER (KW) = 21377.2 Title of case model: Evaporator o/s	GTHR (BTU/KWH) = 7452.0 NUHR (BTU/KWH) = 8708.8 BOILER EFF (%) = 88.56 C W TEMP (F) = 75.00	UNIT 5 PEPSE RUN: 04/17/97 DRAWING DATE: 07/01/96

Figure 6

Use of the evaporator condenser minimizes the thermodynamic losses introduced by the evaporator in this cycle. The heat used for evaporation is returned to the cycle in the evaporator condenser which returns the heat to the deaerator. Since the heat is returned to the same heater from which the evaporator extraction steam normally supplies, there is minimal loss in thermodynamic availability of this steam. Turbine stage pressures and extraction flows are nearly identical in the two heat balances calculated for this cycle.

The improvement in cycle efficiency for removing the evaporator is due almost entirely to elimination of evaporator blowdown losses and losses in heating the water sent to storage (this water enters the cycle at 60 F and exits at 120 F). By the time this water is treated in the condensate cleanup system and sent back to storage it loses its thermal energy picked up in the evaporation process.

Summary of Results from Heat Balance Studies

On a plant total basis (neglecting changes in aux power), Full load NUHR is improved by 9.6 Btu/kwh and full load capacity is increased by 1308 KW by removing the evaporators from service. The following table summarizes the impact on heat rate and net generation at full load.

Summary of Heat Rate and Net Generation Improvement for Removing the Evaporators from Service			
	Unit Rating (MWN)	Heat Rate Effect (Btu/kwh)	Net Gen Increase (KW)
Unit 1	205	-22.7	443
Unit 2	205	-22.7	443
Unit 3	215	-5.8	105
Unit 4	215	-5.8	105
Unit 5	585	-3.2	212
Total Plant	**1425**	**-9.6**	**1308**

Auxiliary Power Requirement of RO System

The reverse osmosis system requires additional pumping power to effect flow through the filter membrane. The estimated pumping power (based on a recently installed system) is 300 hp for a 240 gpm system. With total plant makeup water requirement of 105200 PPH (210 gpm) the increase in additional aux power will be approximately 196 KW. The total plant heat rate increase due to this additional aux power is 1.3 Btu/kwh.

Thus, when considering the impact on aux power, the total plant change in full load NUHR is -8.3 Btu/kwh and the net capacity increase is 1112 KW.

SUMMARY

A heat balance study was conducted using PEPSE to evaluate the performance improvements due to replacing the evaporators with a reverse osmosis system at one of AEP's plant sites. On a total plant basis (with aux power considered), expected change in full load NUHR is -8.3 Btu/kwh and the net capacity increase is 1112 KW.

The improvements on a unit basis were most notable on Units 1 and 2. On these units with evaporators in service, the loss of thermodynamic availability in the extraction steam used for evaporation is significant. The evaporators on Units 3 and 4, introduce less thermodynamic losses to the cycle due to the lower energy steam from the BFPT exhaust used for evaporation. Unit 5 has minimal thermodynamic losses due to use of the evaporator condenser, but has some losses due to evaporator blowdown and heating of the treated water.

Other advantages of the RO system are improved water quality and the ability to produce purified water when the plant is shut down. The water from a RO system is of a higher purity than that from an evaporator system due to the unavoidable carry-over of impurities from the evaporator moisture separator. The improved water quality reduces scaling on the inside of boiler tube surfaces which prevents overheating and increases boiler tube life.

An economic evaluation to determine the benefits of replacing the evaporators with a reverse osmosis system will be performed using the results of the heat balance study. Heat rate and extra generation capacity benefits, operating and maintenance costs, and the cost of installing the RO system will be considered in the economic evaluation which will be used to make a recommendation to management.