Use of PEPSE
for
Thermal Cycle Analysis of Cogeneration Projects

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Abstract

Gulf States Utilities has used PEPSE over six years to study plant operating condition and proposed modifications. In one specific application, the code was employed to determine the feasibility of auxiliary steam service from a cycle originally designed to provide base load electrical service only.

Prospective uses for the steam dictated the flows and steam conditions from the turbine cycle. The PEPSE analysis matched the desired steam quantities and conditions to specific locations in the cycle. Results also indicated what changes to expect in cycle performance and what cycle modifications might be required, thus eliminating some scenarios from further consideration.

The purpose of this paper is to detail the progress of the analysis from general cycle requirements to modified cycle performance.

Introduction

Gulf States Utilities is currently studying the feasibility of supplying process steam to neighboring industrial customers. A task force was created in late 1985 to develop comprehensive testing procedures along with a cost estimate for determining if a unit could be used for this purpose. Various operational scenarios were modeled with the code to outline the limitations and expected problem areas within the cycle when being operated as an extraction turbine. The results of the PEPSE study would be employed in determining the testing procedures and would pinpoint any modifications to the unit which might be necessary prior to conducting the test.

Since the unit's ability to supply the process steam needs to be determined prior to approaching prospective customers, the study examined the effect of providing 400,000 lb/hr of process steam at both 750°F/450 psia and/or 450°F/165 psia. Taking the extraction from the main steam line was eliminated because to both throttle and spray the extraction to meet the process requirements without getting any work out of the steam would be highly inefficient. An extraction of this size from the cold reheat line would have seriously taxed the reheater and for this reason was also eliminated from consideration. The study examined the effect of taking the process from the hot reheat line and/or the crossover line as the conditions at these two points are close to the required process requirements.

A major concern of the study was the accuracy of the PEPSE output when modeling a unit under such abnormal conditions. Typically PEPSE is considered to be quite accurate as long as the unit operates within the normal flow range. A study of this sort truly tests the limits of a code such a PEPSE. Because of the concern as to the reliability of PEPSE to accurately predict conditions throughout the cycle in this operation, hand calculations were performed to predict the effect of the process extractions on the turbine. These hand calculations were based upon setting the various pressures throughout the turbine based on volumetric flow ratio. Sample hand calculations are shown in Figure 1. PEPSE calculates the pressures through the turbine stages based upon the expansion line defined by the conditions at the turbine bowl and exhaust. The conditions at the turbine exhaust are determined by the flow coefficient at the inlet of the downstream stage along with the flow to the downstream stage. It was felt that the hand calculations allowed more flexibility in the flow range and thus were more accurate for this study than the PEPSE calculations through the turbine stages. Since the hand calculations are extremely involved in determining the effect on the entire cycle, i.e., the effect on the feedwater train, they were compared to the PEPSE calculations and where significant differences occurred through the turbine stages the PEPSE model was modified to reflect the results of the hand calculations. This allowed a merging of the two methods and was felt to net the most accurate available predictions as to the effect of this type of project on the total thermal cycle.

Case Descriptions And Modeling Methods

The PEPSE model for this unit had been developed from the full-load 5% over-pressure heat balance for use in evaluating performance test results. Figure 2 is the modified PEPSE flow diagram for this unit. Modifications were made for process extractions to be taken on the main steam, cold reheat, hot reheat and crossover lines to allow for any changes in project philosophies throughout the duration of the study without necessitating model changes. The model was changed to take spray flow for process temperature control from the boiler feed pump and to be capable of returning make-up to either the condenser or between the deaerator and the fourth point feedwater heater. The study examined five scenarios as outlined in Figure 3. All five cases were run at full-load with the extractions coming from the hot reheat and/or the crossover line with the make-up being returned to the condenser and L/D feedwater heater extraction line pressure drops. Since the unit was rarely operated at over-pressure throttle conditions, it was preferable to run some cases at rated conditions. PEPSE was utilized to determine the full-load throttle flow with rated pressure because all heat balances were based on 5% over-pressure. The design case was run with rated throttle pressure controlling throttle flow to achieve an equivalent throttle flow ratio of 1.0, indicative of valves wide open operation. This resultant throttle flow was used in all rated throttle pressure cases.

Hot Reheat Extractions

Cases 1 and 2 represent the cases examining the process steam being supplied from the hot reheat line. Case 1 represents the full-load 5% over-pressure case while Case 2 represents full-load/rated pressure throttle conditions. There was little difference between the two cases in terms of modeling. The change in throttle conditions did not present any particular problems. The initial run for each case took the uncontrolled extraction flow to determine any problems in the remainder of the cycle due to the significant loss of flow. None resulted. The next step, controlled the spray flow to set the process temperature to 750°F. Several tries were usually necessary to determine a close estimate of the amount of extraction flow needed to merge with the spray to net a process flow of 400,000 lb/hr. The additional amount of convergence time necessary to control both the process flow and the spray flow was not considered worthwhile. The real problem in modeling this case was to control the pressure to 450 psia. Initially, the HP exhaust pressure was set to produce the required process pressure along with a pressure drop between the extraction point and the IP inlet. Convergence was not achieved using this approach. The problem was solved by setting the IP bowl pressure and the required pressure drop between the IP and the process extraction point to net the required 450 psia for the process. In order to take this approach, each case required two runs before acceptable results were produced. The first case took the temperature-controlled extraction and determined the IP bowl pressure resultant of the loss of flow. The second run set the IP bowl pressure output by the first run and the required pressure drop between the extraction point and the IP turbine.

Crossover Extractions

Case 3 modeled the crossover extraction with rated throttle conditions. There was no advantage to operating with over-pressure throttle conditions with the crossover extraction so only one crossover case was run. Modeling the crossover extraction presented more problems than did the hot reheat cases. A problem was encountered on the initial run in which the loss of flow to the LP turbine caused the run to fail. The extraction flow was reduced until the case would run. The case converged with the extraction flow lowered to around 200,000 lb/hr but the output was not reasonable in that the LP turbine efficiency was over 100%. Since PEPSE assumes a constant and continuous expansion line through both the IP and LP turbine sections in single-reheat cycles, the pressure buildup is not fed all the way back to the input of the cycle. Instead, all of the excess pressure is seen only by the last stage of the IP turbine forcing abnormally high enthalpies both there and into the first stage of the LP turbine. These high enthalpies caused an unreasonably high efficiency in the first stage of the LP turbine resulting in a total LP efficiency in excess of 100%. To remedy this it was necessary for the IP and LP turbines to operate on separate expansion lines. This was accomplished by adding a psuedo-reheater between the process extraction point and the LP turbine. This reheater did not add any heat to the cycle but defined the unit as a double-reheat cycle which allowed for separate expansion lines for the two turbine sections. This modification allowed the model to take the entire 400,000 lb/hr extraction without any further problems. Since the temperature of the process flow at this point in the case was not higher than the required 450°F, there was no need to set the spray flow controls. As in the hot reheat extraction cases, pressure control was accomplished by designating the bowl pressure of the turbine stage immediately downstream of the extraction point along with the necessary pressure drop between the extraction point and the turbine. Since the pressure control also increased the IP exhaust temperature significantly, the spray flow controls were also employed on this run. This method did not converge. With this case being set up as a double-reheat cycle, the expansion line for the IP turbine was defined by the IP bowl pressure and the LP bowl pressure assuming that the pressure into the LP was the same as the IP exhaust pressure. In this case, that assumption is invalid and as expansion in the first stage of the IP turbine adheres to this expansion line, the second stage is forced to act as a pump to satisfy the process pressure requirements. For PEPSE to accomplish this, the second stage of the IP turbine took flow from the deaerator through the heater extraction line making it impossible to achieve energy balance around the deaerator and convergence was not achieved. In order to force the model to feed the pressure buildup through the turbine stages, it was necessary to redefine the IP turbine characteristics. The second point extraction pressure is normally very close to the required process pressure, so the turbine characteristics were input with the conditions normally occurring at the second point extraction becoming the IP exhaust conditions. The characteristics of the turbine at the second point extraction in the modified case were defined by the design conditions midway from inlet to second point extraction. This allowed for convergence as long as a pressure drop was incorporated into the third point extraction lines to prevent over-pressuring the deaerator. It had already been determined that a valve would be needed in this line for the test. Even though convergence occurred, when the results were compared to the hand calculations it was discovered that the second point extraction pressure predicted by PEPSE was higher than that predicted by the hand calculations. The IP turbine characteristics were again changed to have more work occur in the first stage than the second as predicted by the hand calculations rather than having the second point extraction occur at the midpoint of the IP turbine.

Hot Reheat And Crossover Extractions Simultaneously

Cases 4 and 5 modeled the unit with extractions from both the hot reheat line and the crossover line simultaneously. Case 4 was run with the extractions both at 200,000 lb/hr and 5% over-pressure throttle conditions. Case 5 set the hot reheat extraction at 100,000 lb/hr and the crossover at the 300,000 lb/hr with the throttle conditions at rated pressure and flow with the temperatures at 950 and 900 to control the excess crossover temperature. These two models presented no new problems not encountered in the individual cases. These cases took three runs to get the final output. The first run taking the uncontrolled extractions to get the resulting LP bowl pressure. The second set the LP bowl pressure and the subsequent IP-LP pressure drop to get the necessary IP bowl pressure. The last run set the IP and LP bowl pressures along with both the HP-IP pressure drop and the IP-LP pressure drop.

Results

The results of the PEPSE study are shown in Figures 4 & 5. Several problem areas and subsequent operational limits for the test were revealed by the results. Any cases including a crossover extraction resulted in elevated temperatures at the IP exhaust and crossover line. It was necessary to control these high temperatures by reducing the inlet and reheat temperatures to avoid exceeding material limits in IP exhaust and crossover piping. Cases 3 and 5 reflect reruns of those cases incorporating the temperature requirements. Prior to the study, it had been theorized that a valve would be needed in the third point extraction line when the crossover extraction was taken to avoid over pressuring the deaerator and PEPSE supported this position. All cases have resulted in concern as to whether the heater drains would be capable of passing the increased amount of flow predicted. This was especially prevalent with the first point heater in the hot reheat cases. The study has provided a good basis for developing the testing procedures and has supplied reasonable assumptions for anticipated conditions during the test.

Summary

Although PEPSE was not originally designed to be utilized for studies such as this one, acceptable results can be achieved as long as the limitations of the code are understood. The basic assumptions inherent in any computer code of this type define the limitations of the model. The flexibility of the inputs into PEPSE allow the user to define conditions throughout the cycle where PEPSE cannot, because of its assumption limitations, accurately predict the results. Based upon the results obtained, this study is considered to be acceptable for setting the guidelines for the testing procedures.

Sample Turbine Hand Calculations

Design Conditions

Turbine Stage	24	23	22	21	20	19	18	17	16	15	14
Flow - W	637842	637842	637842	637842	637842	674735	674735	674735	674735	674734	674735
Exit Pres. - P2	77	91.4	108.4	128.6	152.6	181.0	208.7	240.7	277.5	320.0	369.0
Enth. - H2	1326	1340	1359	1377	1396	1416	1432	1449	1466	1482	1501
SP Vol - V2	8.10	6.95	6.10	5.30	4.60	4.00	3.6	3.15	2.85	2.52	2.25
Wv/3600 -	1435	1231	1081	939	815	750	675	590	534	472	422
Diff. Pres. -	14.4	17.0	20.2	24.0	28.4	27.7	32.0	36.8	42.5	49.0	56.5
Inlet Pres. - P1	91.4	108.4	128.6	152.6	181.0	208.7	240.7	277.5	320.0	369.0	425.5
Enth. - H1	1340	1359	1377	1396	1416	1432	1449	1466	1482	1501	1522

Case #3 - 950/900 F, 1465 PSIA, 400,000 @ XO

Turbine Stage	24	23	22	21	20	19	18	17	16	15	14
Flow - W	626680	626680	626680	626680	626680	680963	680963	680963	680963	680963	680963
Exit Pres. - P2	165.0	168.3	173.6	181.2	192.4	208.5	227.6	251.2	281.7	317.5	360.9
Enth. - H2	1358	1360	1363	1369	1377	1386	1395	1406	1419	1432	1445
SP Vol - V2	3.97	3.92	3.81	3.69	3.52	3.29	3.07	2.84	2.59	2.35	2.12
Wv/3600 -	691	682	663	642	613	622	581	537	490	445	401
Diff. Pres. -	3.3	5.2	7.6	11.2	16.1	19.1	23.7	30.5	35.7	43.4	51.1
Inlet Pres -	168.3	173.6	181.2	192.4	208.5	227.6	251.2	281.7	317.5	360.9	412.0
Enth. - H1	1360	1363	1369	1377	1386	1395	1406	1419	1432	1445	1464

Calculations Based on Volumetric Flow Ratio:

$$P_{ACT} = P_{DES} \; [(Wv)^2_{ACT}/(Wv)^2_{DES}]$$

Figure 1

Modified PEPSE Flow Diagram

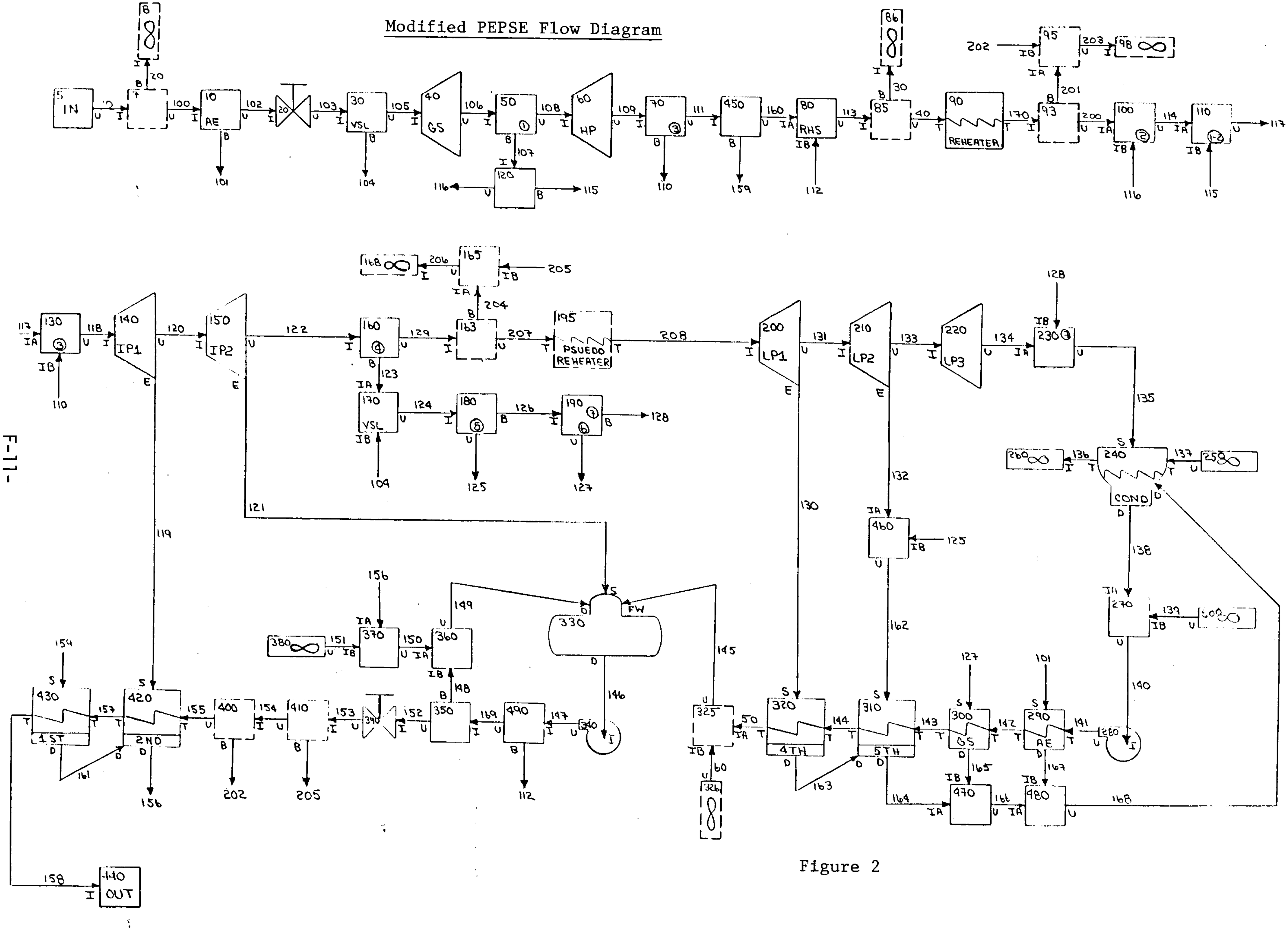

Figure 2

Case Description

	Throttle Conditions			Process Conditions					
				Hot Reheat			Crossover		
	Flow LB/HR	Temp F	Press PSIA	Flow LB/HR	Temp F	Press PSIA	Flow LB/HR	Temp F	Press PSIA
Case #1	787,600	1000/1000	1539.7	410,000	750.0	450.0	-	-	-
Case #2	748,440	1000/1000	1464.7	400,000	750.0	450.0	-	-	-
Case #3	748,440	950/900	1464.7	-	-	-	400,000	450.0	165.0
Case #4	787,600	1000/1000	1539.7	200,000	750.0	450.0	200,000	450.0	165.0
Case #5	748,440	950/900	1464.7	100,000	750.0	450.0	300,000	450.0	165.0

Figure 3

TURBINE CYCLE RESULTS

		Main Steam	HP Exhaust	Hot Reheat	HRH Extract	HRH Process	IP Bowl	X.O. Extract	X.O. Process	Cross Over	Turbine Exhaust	Net MW
VWO Rated	Flow	748,440	733,477	659,845	0	0	672,368	0	0	600,049	530,303	
	Pres.	1464.7	479.8	432.3	-	-	423.6	-	-	76.3	1.2	
	Temp.	1000.0	718.6	1000.0	-	-	997.1	-	-	570.5	108.7	
	Enth.	1491.2	1369.2	1522.3	-	-	1521.0	-	-	1316.6	1060.9	104.2
VWO 5% O.P.	Flow	787,600	772,630	694,680	0	0	694,680	0	0	631,440	551,740	
	Pres.	1539.7	515.4	470.1	-	-	470.1	-	-	95.7	1.2	
	Temp.	1000.0	718.1	1000.0	-	-	1000.0	-	-	590.2	107.9	
	Enth.	1488.9	1367.1	1520.9	-	-	1520.9	-	-	1325.0	1041.3	109.0
Case #1	Flow	787,600	772,038	643,845	368,000	410,104	288,968	0	0	225,784	176,982	
	Pres.	1539.7	499.4	450.0	450.0	450.0	219.6	-	-	27.6	1.2	
	Temp.	1000.0	715.5	1000.0	1000.0	749.8	981.1	-	-	488.0	108.7	
	Enth.	1488.8	1366.4	1521.8	1521.8	1387.8	1518.6	-	-	1280.4	1076.1	55.5
Case #2	Flow	748,440	733,477	607,729	359,000	399,832	261,252	0	0	202,608	159,097	
	Pres.	1464.7	499.4	450.0	450.0	450.0	203.4	-	-	24.7	1.2	
	Temp.	1000.0	727.6	1000.0	1000.0	749.9	980.1	-	-	480.6	108.7	
	Enth.	1491.2	1373.1	1521.8	1521.8	1387.8	1518.6	-	-	1277.1	1082.3	49.9
Case #3	Flow	748,440	733,477	668,440	0	0	680,963	358,000	399,887	208,939	164,171	
	Pres.	1464.7	467.7	421.4	-	-	413.0	165.0	165.0	22.6	1.2	
	Temp.	950.0	670.0	900.0	-	-	897.9	668.3	450.0	652.1	148.9	
	Enth.	1461.2	1342.7	1469.3	-	-	1468.5	1360.0	1245.4	1360.0	1126.9	55.7
Case #4	Flow	787,600	772,038	687,822	178,500	200,057	522,444	169,000	199,927	256,496	202,917	
	Pres.	1539.7	499.4	450.0	450.0	450.0	352.0	165.0	165.0	32.4	1.2	
	Temp.	1000.0	715.5	1000.0	1000.0	750.0	991.3	790.6	450.0	779.4	167.4	
	Enth.	1488.8	1366.4	1521.8	1521.8	1387.9	1520.0	1422.2	1245.4	1422.2	1135.3	58.2
Case #5	Flow	748,440	733,477	654,890	93,250	100,012	574,162	265,000	300,350	203,818	160,050	
	Pres.	1464.7	499.4	450.0	450.0	450.0	359.4	165.0	165.0	24.1	1.2	
	Temp.	950.0	684.1	900.0	900.0	750.0	892.2	696.8	450.3	681.9	157.4	
	Enth.	1461.2	1348.8	1468.3	1468.3	1387.9	1467.4	1374.5	1245.5	1374.5	1130.8	49.1

Figure 4

FEEDWATER EXTRACTION RESULTS

		1st Pt. Extract.	2nd Pt. Extract.	3rd Pt. Extract.	4th Pt. Extract.	5th Pt. Extract.
VWO Rated	Flow	73,632	36,746	34,906	39,862	29,883
	Pres.	479.8	180.3	76.3	28.6	7.2
	Temp.	718.6	770.9	570.5	384.5	178.1
	Enth.	1369.2	1411.5	1316.6	1230.5	1133.8
VWO 5%-O.P.	Flow	77,950	37,340	38,330	42,600	37,100
	Pres.	515.4	205.1	95.7	30.4	7.5
	Temp.	718.1	781.9	590.2	396.4	179.3
	Enth.	1367.1	1416.0	1325.0	1236.0	1138.0
Case #1	Flow	128,192	27,606	34,879	33,269	15,533
	Pres.	499.4	72.2	27.6	9.3	2.3
	Temp.	715.5	698.1	488.0	296.2	131.4
	Enth.	1366.4	1380.0	1280.4	1192.1	1103.0
Case #2	Flow	125,748	25,752	32,226	30,598	12,912
	Pres.	499.4	64.9	24.7	8.3	2.1
	Temp.	727.6	690.4	480.6	289.1	127.3
	Enth.	1373.1	1376.5	1277.1	1189.0	1101.0
Case #3	Flow	65,037	54,283	59,075	30,318	14,449
	Pres.	467.7	211.4	165.0	9.6	2.3
	Temp.	670.0	727.1	668.3	473.1	229.2
	Enth.	1342.7	1387.6	1360.0	1275.1	1163.0
Case #4	Flow	84,216	34,993	61,255	34,010	19,570
	Pres.	499.4	170.4	165.0	12.6	3.0
	Temp.	715.5	798.7	790.6	563.4	297.3
	Enth.	1366.4	1426.1	1422.2	1318.0	1194.0
Case #5	Flow	78,588	38,226	66,451	29,733	14,036
	Pres.	499.4	180.3	165.0	9.4	2.3
	Temp.	684.1	717.9	696.8	481.7	235.8
	Enth.	1348.8	1384.4	1374.5	1279.2	1166.0

Figure 5