A Thermodynamic Analysis of Five Compressed Air Energy Storage Cycles

J. A. Fort

March 1983

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Pacific Northwest Laboratory
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FOREWORD

Compressed air energy storage (CAES) is a technique for supplying electric power to meet peak load requirements of electric utility systems. It incorporates a modified state-of-the-art gas turbine and an underground reservoir--an aquifer, a salt cavity, or a mined hard rock cavern. The compressor and turbine sections of the gas turbine are alternately coupled to a motor/generator. During nocturnal and weekend off-peak periods, low-cost power from base load plants using coal or nuclear fuels would be used to drive motors to compress air, which would be stored in the underground cavern. During the subsequent diurnal peak-load periods, the compressed air would be withdrawn from storage, mixed with fuel, burned, and expanded through the turbines to generate peak power. This concept reduces the consumption of premium fuels by more than 60% for conventional systems. Some advanced or second-generation CAES concepts would require no petroleum fuels.

In 1975, the Pacific Northwest Laboratory (PNL) was selected as DOE's lead laboratory in researching and developing CAES technology. As lead laboratory, PNL has managed a comprehensive research and development program to advance CAES to the point of adoption by the private sector.

Based on this research, several alternative designs have been proposed for second-generation CAES plants. This document pictorially represents the thermodynamic cycle performance characteristics of five of these systems. Some use alternative fuels or energy sources, while others use thermal energy storage to capture and reuse the heat of compression. To evaluate these designs, thermodynamic cycle analyses must be performed.

Therefore, a computer code was developed specifically to perform these cycle analyses. The Compressed Air Energy Storage Cycle Analysis Program (CAESCAP code) calculates property values and performance parameters for thermodynamic cycles using a variety of working fluids. The features and methodology of the PNL-developed CAESCAP code were documented previously in PNL-4486 (Fort 1982).

The analyses of five CAES plant cycles reported herein were performed using the CAESCAP code. The resulting availability and energy flow diagrams for each plant cycle are intended to increase understanding of the overall thermodynamic performance characteristics of the various plant configurations. It is hoped that this understanding will stimulate development of more efficient and effective CAES systems.

L. D. Kannberg
Manager
Underground Energy Storage Program

SUMMARY

One important aspect of the Compressed Air Energy Storage (CAES) Program is the evaluation of alternative CAES plant designs. The thermodynamic performance of the various configurations is particularly critical to the successful demonstration of CAES as an economically feasible energy storage option.

A computer code, the Compressed Air Energy Storage Cycle Analysis Program (CAESCAP), was developed in 1982 at the Pacific Northwest Laboratory. This code was designed specifically to calculate overall thermodynamic performance of proposed CAES system configurations. The results of applying this code to the analysis of five CAES plant designs are presented in this report. The designs analyzed were:

- conventional CAES
- adiabatic CAES
- hybrid CAES
- pressurized fluidized bed CAES
- direct coupled steam-CAES.

Inputs to the code were based on published reports describing each plant cycle. For each cycle analyzed, CAESCAP calculated the thermodynamic station conditions and individual component efficiencies, as well as overall cycle performance parameter values. These data were then used to diagram the availability and energy flow for each of the five cycles.

The resulting diagrams graphically illustrate the overall thermodynamic performance inherent in each plant configuration, and enable a more accurate and complete understanding of each design.

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A THERMODYNAMIC ANALYSIS OF FIVE COMPRESSED AIR ENERGY STORAGE CYCLES

INTRODUCTION

Compressed air energy storage (CAES) is one promising alternative for supplying peaking power capability to electric utilities. In a CAES plant, excess base-load generation capacity is used to compress air for storage in an underground reservoir. During periods of peak electrical demand, air is extracted from storage, heated, and expanded in a turbine that drives a generator.

Compressed air energy storage plants can be classified as either conventional or second-generation. Conventional CAES plants use petroleum fuel for air heating. This is a disadvantage because of the cost and uncertain future availability of these fuels. Second-generation CAES concepts are being developed to reduce or eliminate this dependence on petroleum fuels.

Several alternative designs have been proposed for second-generation CAES plants. Some use alternative fuels or energy sources, and others use thermal energy storage to capture and reuse the heat of compression. To aid in the comparison and evaluation of these various designs, thermodynamic cycle analyses must be performed. This report describes the analyses of five CAES plant cycles.

These analyses were performed using the PNL-developed Compressed Air Energy Storage Cycle Analysis Program, CAESCAP. The features, methodology and use of the CAESCAP code have been described in detail by Fort (1982). Inputs to the computer program were based on published reports describing each cycle. An attempt was made to match reported conditions; in most cases, this was accomplished. Any discrepancies or necessary assumptions are noted. Included in this report for each cycle analyzed are the thermodynamic station conditions and component efficiencies, overall cycle performance parameter values, and diagrams showing the availability and energy flows.

CYCLE ANALYSES

The CAES cycles analyzed were:

- conventional CAES
- adiabatic CAES
- hybrid CAES
- pressurized fluidized bed CAES
- direct coupled steam-CAES.

The calculated performance parameters for each cycle are given in Table 1. These parameters were calculated using standard equations, which are described in Fort (1982). A motor and generator efficiency of 0.98 was assumed. Turbine power was charged for plant auxiliaries as follows:

- premium fueled 1.5%
- coal fired 5.0%
- no fuel 2.0%

TABLE 1. Cycle Performance Parameters

<u>Cycle</u>	<u>Charge Energy Factor</u>	<u>Generation Heat Rate (Btu/kWh)</u>	<u>Round Trip Heat Rate (Btu/kWh)</u>
Conventional	1.35	3,960	11,375
Adiabatic	0.66	0	15,200
Hybrid	1.03	2,820	12,500
PFBC	1.08	4,220	13,500
Direct coupled steam ^(a)	1.44	3,460	14,200 ^(b)

(a) Performance parameters as well as the cycle analysis for this concept were based on preliminary studies that lack detailed information. This should be kept in mind when using these values.

(b) For the direct coupled steam cycle, compression heat rate included heat input to the thermal energy storage as well as to the steam cycle. This resulted in a higher round-trip heat rate than was previously reported where the thermal energy storage input was apparently left out.

For all cycles, 2% of compression power was charged for plant auxiliaries used during the compression period.

CONVENTIONAL CAES

This cycle analysis was based on the conceptual design performed by Acres American, Inc. (1981b). The cycle diagram is shown in Figure 1. Of the two alternative turbine arrangements described in the Acres report, the 58-bar option was selected for analysis. Component efficiencies were calculated to match the reported inlet and outlet thermodynamic conditions. Sufficient information was not available to calculate the high pressure turbine efficiency; therefore, it was assumed to be the same as that of the low pressure turbine.

FIGURE 1. Conventional CAES Cycle Diagram

The cycle station conditions and component efficiencies calculated by the CAESCAP program are shown in Figure 2. The energy and availability flow diagrams for the conventional CAES cycle are presented in Figures 3 and 4, respectively. Note that the auxiliary loads used in calculating the performance parameters of Table 1 were not included in either flow diagram. For the energy flow diagram the energy at a station was calculated as

$$E = (H - H_{\text{ref}}) Wt$$

where E is the energy
 H is the station enthalpy
 H_{ref} is a reference enthalpy
 W is the flow rate at the station
 t is the charge or discharge time depending on the station location.

For all cycles, the air inlet enthalpy was used as the reference enthalpy, H_{ref} . For the availability flow diagram, the availability at a station was calculated as

$$A = (\psi - \psi_{\text{ref}}) Wt$$

where A is the availability
 ψ is the station availability per unit mass
 W, t are as described above.

The definition for the availability per unit mass, ψ , was taken from Van Wylen and Sonntag (1976):

$$\psi = (h - T_0 S + \frac{v^2}{2} + gz) - (h_0 - T_0 S_0 + gz_0)$$

This is sometimes referred to as the energy per unit mass. When kinetic and potential energy contributions are neglected, the above reduces to

$$\psi = h - h_0 - T_0 (S - S_0).$$

CONVENTIONAL CAES										
STATION	PRESSURE PSIA	ENTHALPY BTU/LB	TEMPERATURE DEG.F	ENTROPY BTU/LB-DEG.F	AVAIL.WORK BTU/LB	QUALITY	MOL.WT.	FLOW PPS	POWER RTU/SEC	E
1	14.700	123.92	59.00	.0000	.12	.0000	28.966	661.000	.00	.00
2	95.400	231.96	503.93	.0000	95.70	.0000	28.966	661.000	71418.27	.81
3	94.446	138.16	120.00	.0000	68.73	.0000	28.966	661.000	-62000.48	.00
4	174.000	171.14	256.98	.0000	96.57	.0000	28.966	661.000	21795.07	.80
5	172.260	137.76	120.00	.0000	90.84	.0000	28.966	661.000	-22064.78	.00
6	294.000	165.83	236.98	.0000	114.73	.0000	28.966	661.000	18558.76	.81
7	291.060	137.16	120.00	.0000	110.16	.0000	28.966	661.000	-18953.43	.00
8	567.000	173.89	272.99	.0000	141.10	.0000	28.966	661.000	24278.73	.79
9	561.330	135.77	120.00	.0000	134.31	.0000	28.966	661.000	-25200.38	.00
10	1015.000	166.48	247.98	.0000	161.29	.0000	28.966	661.000	20300.61	.82
11	1004.850	139.02	140.00	.0000	156.46	.0000	28.966	661.000	-18149.96	.00
12	950.000	139.02	139.30	.0000	154.30	.0000	28.966	661.000	.00	.00
13	921.000	275.78	680.00	.0000	201.20	.0000	28.966	661.000	90400.01	.00
14	841.000	275.78	679.83	.0000	197.77	1.0000	28.966	661.000	.00	.00
15	812.000	364.62	1020.09	.0000	248.23	.0000	28.966	664.291	59427.93	1.00
25	.000	150.00	.00	.0000	.00	1.0000	28.966	3.291	.00	.00
16	160.000	249.43	574.38	.0000	122.77	1.0000	28.966	664.291	76518.17	.86
17	160.000	535.96	1650.43	.0000	306.93	.0000	28.966	675.062	194497.13	1.00
26	.000	150.00	.00	.0000	.00	1.0000	28.966	10.771	.00	.00
18	15.100	312.98	823.93	.0000	69.42	.0000	28.966	675.062	150527.74	.86
19	14.700	179.07	287.41	.0000	7.54	.0000	28.966	675.062	-90400.01	.79
50	.000	.00	.00	.0000	.0018057	.0000	28.966	.000	.00	.00

FIGURE 2. Conventional CAES Thermodynamic Conditions

KEY

- ENERGY FLOW
- ENERGY LOSSES

KEY

AVAILABILITY FLOW

AVAILABILITY LOSSES

This method of calculating the availability per unit mass differs from that described in Fort (1982). At that time the CAESCAP code calculated ϕ rather than ψ , where ϕ is defined by Van Wylen and Sonntag (1976) as

$$\phi = u - u_0 + P_0(v - v_0) - T_0(S - S_0)$$

which can be rewritten as

$$\phi = (h - h_0) - v(p - p_0) - T_0(S - S_0)$$

However, ϕ is the specific availability for a closed system and ψ is the more appropriate parameter for an open system such as a thermodynamic cycle. The CAESCAP calculation has since been updated to calculate ψ rather than ϕ . The values of ψ are printed along with the other thermodynamic properties in Figure 2.

ADIABATIC CAES

This cycle analysis was based on the conceptual design performed by Acres American, Inc. (1981a). The cycle diagram is shown in Figure 5. Due to a lack of information on the two high pressure compressors, the two units were treated as one for this analysis. Temperatures at Stations 3 and 10 were varied from those reported by Acres American, Inc. (1981a) to achieve the specified thermal energy storage effectiveness and approach temperature difference values. In addition, discharge flow rate was set equal to charging flow rate.

The calculated station conditions are shown in Figure 6. The energy and availability flow diagrams are given in Figures 7 and 8, respectively.

HYBRID CAES

The A-5 hybrid CAES cycle as described by Glendenning et al. (1979) was analyzed. The cycle diagram is presented in Figure 9. To maintain an energy balance across the recuperator, the temperature at Station 16 was varied from the reported value. Also, the compressor outlet temperature at Station 5 was varied from the reported value to maintain a reasonable compressor efficiency.

FIGURE 5. Adiabatic CAES Cycle Diagram

ADIABATIC CAES										
STATION	PRESSURE PSIA	ENTHALPY BTU/LB	TEMPERATURE DEG.F	ENTROPY BTU/LB-DEG.F	AVAIL. WORK BTU/LB	QUALITY	MOL.WT.	FLOW PPS	POWER BTU/SEC	ϵ
1	14.200	131.38	90.00	.0000	-1.28	.0000	28.966	650.000	.00	.00
2	226.000	326.73	876.89	.0000	177.32	.0000	28.966	650.000	126981.25	.81
3	211.000	223.18	469.00	.0000	121.32	.0000	28.966	650.000	-67311.06	.00
4	206.000	165.93	236.00	.0000	101.61	.0000	28.966	650.000	-37213.00	.00
5	1215.000	314.62	829.54	.0000	233.17	.0000	28.966	650.000	96652.59	.73
8	1190.000	134.50	125.00	.0000	162.65	.0000	28.966	650.000	-117080.74	.00
10	1150.000	128.10	100.00	.0000	161.06	.0000	28.966	650.000	-4157.52	.00
11	1125.000	308.23	805.03	.0000	226.58	.0000	28.966	650.000	117080.74	.97
13	241.000	219.39	454.01	.0000	124.67	.0000	28.966	650.000	57745.08	.81
15	225.000	322.94	862.29	.0000	174.91	.0000	28.966	650.000	67311.06	.97
16	14.700	166.00	233.52	.0000	4.29	.0000	28.966	650.000	102012.05	.90

FIGURE 6. Adiabatic CAES Thermodynamic Condition

FIGURE 9. Hybrid CAES Cycle Diagram

The calculated station conditions are shown in Figure 10. The energy and availability flow diagrams are given in Figures 11 and 12, respectively.

PRESSURIZED FLUIDIZED BED COMBUSTION CAES

This analysis of a CAES cycle incorporating a pressurized fluid bed combustor is based on a conceptual design by Giramonti et al. (1980). The cycle diagram is shown in Figure 13. In this analysis the fluid bed combustor was treated as a fueled combustor because design calculations performed in the fluid bed combustor model were not required.

The calculated station conditions are presented in Figure 14. The energy and availability flow diagrams are given in Figures 15 and 16, respectively.

HYBRID CAES										
STATION	PRESSURE PSIA	ENTHALPY BTU/LB	TEMPERATURE DEG.F	ENTROPY BTU/LB-DEG.F	AVAIL.WORK BTU/LB	QUALITY	MOL.WT.	FLOW PPS	POWER BTU/SEC	E
1	14.500	123.92	59.00	.0000	-.39	.0000	28.966	661.000	.00	.00
2	232.000	312.00	819.98	.0000	169.68	.0000	28.966	661.000	124321.47	.80
3	226.000	195.43	356.67	.0000	113.37	.0000	28.966	661.000	-77051.41	.00
4	223.740	132.26	98.60	.0000	100.24	.0000	28.966	661.000	-41759.48	.00
5	493.000	170.99	260.45	.0000	135.14	.0000	28.966	661.000	25602.90	.87
6	488.070	130.76	98.60	.0000	128.91	.0000	28.966	661.000	-26588.73	.00
7	1026.000	166.54	248.32	.0000	161.72	.0000	28.966	661.000	23645.82	.87
8	1015.740	128.27	98.60	.0000	156.28	.0000	28.966	661.000	-25294.46	.00
9	1015.740	124.98	86.00	.0000	156.26	.0000	28.966	661.000	-2173.45	.00
10	995.425	257.39	608.00	.0000	194.86	.0000	28.966	661.000	87524.66	.00
11	624.000	257.39	607.35	.0000	177.22	.0000	28.966	661.000	.00	.00
13	156.727	186.15	318.18	.0000	96.84	.0000	28.966	661.000	47095.07	.85
14	150.927	302.71	783.99	.0000	148.48	.0000	28.966	661.000	77051.41	.93
15	150.927	536.31	1652.00	.0000	305.01	.0000	28.966	661.000	154410.14	1.00
16	15.100	312.95	823.82	.0000	69.41	.0000	28.966	661.000	147644.21	.88
17	14.700	180.54	293.47	.0000	7.95	.0000	28.966	661.000	-87524.66	.72

FIGURE 10. Hybrid CAES Thermodynamic Conditions

FIGURE 13. Pressurized Fluidized Bed Combustion CAES Cycle Diagram

DIRECT COUPLED STEAM-CAES

This analysis of a steam power plant with direct coupled compressed air energy storage is based on reports by Drost and Reilly (1981) and Sadala (1980). The compression and generation modes were analyzed separately for this cycle. Cycle diagrams for the compression and generation modes are given in Figures 17 and 18, respectively. Due to a lack of specific information, extraction steam for feedwater heaters was assumed to have properties of the turbine outlet. Also the difference in flow rates entering and leaving the condenser was neglected and the entering flow rate was used.

The calculated station conditions are given in Figure 19 for the compression mode and Figure 20 for the generation mode. By comparing conditions at Stations 12 and 33 in Figure 19 and Stations 7 and 32 in Figure 20, it is apparent that the steam cycle does not close thermodynamically. This is assumed to be the result of the simplified extraction steam modeling, which cannot be improved without more information. Also note that the pressures at Stations 32 and 33 are unreasonably low. This is due to the flow mixing model which assumes

PFBC CAES										
STATION	PRESSURE PSIA	ENTHALPY BTU/LB	TEMPERATURE DEG.F	ENTROPY BTU/LB-DEG.F	AVAIL.WORK BTU/LB	QUALITY	MOL.WT.	FLOW PPS	POWER RTU/SEC	E
1	14.700	123.84	58.70	.0000	.12	.0000	28.966	761.800	.00	.00
2	14.600	123.84	58.67	.0000	-.12	.0000	28.966	761.800	.00	.00
3	60.200	193.03	345.34	.0000	63.70	.0000	28.966	761.800	52705.54	.90
4	59.000	148.25	160.90	.0000	52.37	.0000	28.966	761.800	-34116.28	.00
5	243.800	230.89	500.39	.0000	129.93	.0000	28.966	761.800	62957.15	.90
6	240.900	157.00	200.00	.0000	105.60	.0000	28.966	761.800	-56292.35	.00
7	469.800	200.03	377.54	.0000	142.12	.0000	28.966	761.800	32785.98	.77
8	464.800	156.19	200.00	.0000	129.85	.0000	28.966	761.800	-33401.82	.00
9	999.800	207.11	409.29	.0000	173.14	.0000	28.966	761.800	38796.87	.75
10	989.800	133.92	120.00	.0000	155.51	.0000	28.966	761.800	-55758.67	.00
11	978.100	133.92	119.92	.0000	155.03	.0000	28.966	761.800	.00	.00
12	948.100	134.08	120.00	.0000	153.88	.0000	28.966	731.300	.00	.00
13	938.100	134.08	119.93	.0000	153.46	.0000	28.966	731.300	.00	.00
14	918.100	232.02	507.50	.0000	180.05	.0000	28.966	731.300	71418.36	.00
15	888.100	232.02	507.69	.0000	178.74	.0000	28.966	731.300	.00	.00
16	225.400	169.26	250.00	.0000	105.68	.0000	28.966	709.500	45895.44	.83
24	225.400	169.26	250.00	.0000	105.68	.0000	28.966	21.800	.00	.00
25	225.400	169.26	250.00	.0000	105.68	.0000	28.966	21.800	.00	.00
17	220.400	169.26	249.93	.0000	104.85	1.0000	28.966	709.500	.00	.00
18	201.300	510.75	1560.10	.0000	296.80	.0000	28.966	730.411	249835.54	1.00
22	.000	150.00	.00	.0000	.00	1.0000	28.966	20.911	.00	.00
19	199.300	510.75	1560.11	.0000	296.43	.0000	28.966	730.411	.00	.00
20	15.200	277.02	683.59	.0000	49.77	.0000	28.966	746.805	170722.52	.89
26	15.200	277.02	683.59	.0000	49.77	.0000	28.966	713.505	.00	.00
23	15.200	277.02	683.59	.0000	49.77	.0000	28.966	33.300	.00	.00
21	14.900	176.64	277.44	.0000	7.38	.0000	28.966	713.505	-71618.36	.72
50	.000	.00	.00	.0000	.0011947.2832	.0000	28.966	.000	.00	.00

FIGURE 14. Pressurized Fluidized Bed Combustion CAES Thermodynamic Conditions

FIGURE 15. ENERGY FLOWS FOR A FLUIDIZED BED COMBUSTION CAES PLANT

FIGURE 17. Direct Coupled Steam-CAES - Compression Mode

FIGURE 18. Direct Coupled Steam-CAES - Generation Mode

CAES / DIRECT COUPLED STEAM - COMPRESSION MODE										
STATION	PRESSURE PSIA	ENTHALPY BTU/LB	TEMPERATURE DEG.F	ENTROPY BTU/LB-DEG.F	AVAIL.WORK BTU/LB	QUALITY	MOL.WT.	FLOW PPS	POWER BTU/SEC	E
1	14.700	123.92	59.00	.0000	.12	.0000	28.966	641.800	.00	.00
2	61.000	193.82	348.60	.0000	64.45	.0000	28.966	641.800	44865.95	.89
3	60.400	175.57	273.60	.0000	58.67	.0000	28.966	641.800	-11713.54	.00
4	59.800	157.71	200.00	.0000	54.32	.0000	28.966	641.800	-11463.48	.00
5	250.000	246.43	562.72	.0000	137.88	.0000	28.966	641.800	56941.00	.90
6	247.500	228.11	489.10	.0000	129.31	.0000	28.966	641.800	-11757.16	.00
7	245.000	156.98	200.00	.0000	106.23	.0000	28.966	641.800	-45653.06	.00
8	1020.000	260.34	619.72	.0000	197.22	.0000	28.966	641.800	66335.37	.77
9	1009.900	242.15	547.90	.0000	188.20	.0000	28.966	641.800	-11674.10	.00
10	1000.000	135.17	125.00	.0000	155.98	.0000	28.966	641.800	-68656.67	.00
12	2683.000	453.76	470.00	.6451	.00	.0000	18.016	312.400	.00	.00
13	2415.000	1460.38	1000.00	1.5322	.00	1.0000	18.016	312.400	314469.28	.00
23	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	312.400	47371.96	.83
14	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	274.000	.00	.00
24	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	38.400	.00	.00
15	477.400	1520.99	1000.00	1.7426	.00	1.0000	18.016	274.000	58153.76	.00
25	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	274.000	46530.72	.88
16	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	251.100	.00	.00
26	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	22.900	.00	.00
17	1.700	1055.67	120.16	1.8336	.00	.9435	18.016	251.100	74198.20	.88
11	1.700	47.10	79.05	.0915	.00	.0000	18.016	251.100	-253252.80	.00
29	2683.000	57.70	82.42	.0964	.00	.0000	18.016	251.100	2663.09	.75
30	2683.000	104.19	129.48	.1786	.00	.0000	18.016	251.100	11674.10	.13
31	2683.000	151.02	176.72	.2551	.00	.0000	18.016	251.100	11757.15	.17
32	2683.000	197.66	223.55	.3258	.00	.0000	18.016	251.100	11713.54	.44
33	114.300	418.79	337.63	.6251	.00	.1249	18.016	312.400	.00	.00

FIGURE 19. Direct Coupled Steam-CAES Thermodynamic Conditions - Compression Mode

CAES / DIRECT COUPLED STEAM - GENERATION MODE										
STATION	PRESSURE PSIA	ENTHALPY BTU/LB	TEMPERATURE DEG.F	ENTROPY BTU/LB-DEG.F	AVAIL.WORK BTU/LB	QUALITY	MOL.WT.	FLOW PPS	POWER RTU/SEC	E
1	970.000	135.29	125.00	.0000	154.82	.0000	28.966	1388.900	.00	.00
2	970.000	359.33	1000.00	.0000	251.57	.0000	28.966	1388.900	311171.57	.00
3	190.000	239.31	533.96	.0000	124.43	.0000	28.966	1388.900	166493.11	.91
4	186.000	358.86	1000.00	.0000	189.70	.0000	28.966	1388.900	166036.76	.00
5	14.900	193.57	347.07	.0000	12.43	.0000	28.966	1388.900	229567.79	.90
7	2683.000	453.76	470.00	.6451	.00	.0000	18.016	312.400	.00	.00
8	2415.000	1460.38	1000.00	1.5322	.00	1.0000	18.016	312.400	314469.28	.00
23	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	312.400	47171.96	.83
9	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	274.000	.00	.00
24	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	38.400	.00	.00
10	477.400	1520.99	1000.00	1.7426	.00	1.0000	18.016	274.000	58153.76	.00
25	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	274.000	46530.72	.88
11	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	251.100	.00	.00
26	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	22.900	.00	.00
27	1.700	1055.67	120.16	1.8336	.00	.9435	18.016	251.100	74198.20	.88
12	1.700	1055.67	120.16	1.8336	.00	.9435	18.016	205.700	.00	.00
28	1.700	1055.67	120.16	1.8336	.00	.9435	18.016	45.400	.00	.00
6	1.700	47.10	79.05	.0915	.00	.0000	18.016	205.700-207463.56	.00	.00
31	2683.000	57.70	82.42	.0964	.00	.0000	18.016	205.700	2181.59	.75
32	1.700	451.33	120.16	.7913	.00	.3542	18.016	312.400	.00	.00

FIGURE 20. Direct Coupled Steam-CAES Thermodynamic Conditions - Generation Mode

that the outlet flow pressure is equal to the lowest inlet flow pressure. The energy and availability flow diagrams are given in Figures 21 and 22, respectively. There is an obvious discontinuity in both energy and availability flows across the cavern and thermal energy storage. This is due to the difference between charge and discharge air flow rates. During generation, the air discharge flow rate from the cavern is higher than the charging rate during compression. However, the steam cycle operates at a constant flow rate during both compression and generation. For the steam cycle availability calculations, the reference enthalpy was that of the condensor exit.

A

C O M P R T I O N

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