CAESCAP: A Computer Code for Compressed Air Energy Storage Plant Cycle Analysis

J. A. Fort

October 1982

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PLANT CYCLE ANALYSIS

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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 During the subsequent diurnal peak-load periods, the compressed air would be withdrawn from storage, mixed with fuel, burned, and expanded through the turbines to generate peak power.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. 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. This report documents the features, methodology and use of the PNL-developed CAESCAP code.

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SUMMARY

The analysis code, CAESCAP, was developed at the Pacific Northwest Laboratory to aid in comparing and evaluating proposed compressed air energy storage (CAES) cycles. Input consists of component parameters and working fluid conditions at points along a cycle. Given these inputs the code calculates thermodynamic properties at each point and then calculates overall cycle performance. Working fluid capabilities include steam, air, nitrogen, and parahydrogen.

The CAESCAP code was used to analyze a variety of CAES cycles. The combination of **straightforward** input and flexible design make the code easy and inexpensive to use.

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CAESCAP: A COMPUTER CODE FOR COMPRESSED AIR ENERGY STORAGE
PLANT CYCLE ANALYSIS

1.0 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 a computer code that was developed to perform these cycle analyses.

The code development work was conducted at the Pacific Northwest Laboratory (PNL) as part of the Compressed Air Energy Storage Program sponsored by the U.S. Department of Energy. The PNL-developed Compressed Air Energy Storage Cycle Analysis Program, or CAESCAP, is based on an Atomic International code (Hessler et al. 1964). The CAESCAP code calculates property values and performance parameters for thermodynamic cycles using steam, air, nitrogen and parahydrogen as working fluids.

This report describes the features, methodology and use of the CAESCAP code. Section 2.0 briefly describes the overall operation of

the code. In Section 3.0, each of the component models, analysis features, and property libraries is described. Section 4.0 provides some comments on code use. Appendix A contains a code input guide; five CAES plant analyses are presented in Appendix B to serve as samples.

2.0 GENERAL CODE DESCRIPTION

The CAESCAP code calculates working fluid properties and performance parameters for a CAES system thermodynamic cycle. Input describes the thermodynamic operations and working fluid conditions at points throughout the cycle. The code responds with the thermodynamic properties at each point or station. In addition, the performance of individual operations as well as the overall cycle performance is calculated.

The code is capable of modeling CAES systems composed of these components:

- multistage axial flow turbine
- multistage compressor
- multistage pump
- counterflow heat exchanger
- combustor
- fluid bed combustor
- entrained flow coal gasifier
- phase separator
- flow split, mix or throttle.

In general, the component models consist of simple thermodynamic relationships and energy balances. Only the turbine, compressor and pump models have options for more detailed design calculations. These options were not used in the current study, but their description is included for future reference. Furthermore, no single model is devoted to ductwork or piping, but their effects may be included in available component models. For example, pressure drop can be combined with that of an adjacent component and heat loss may be modeled with the heat exchanger model. These component models are discussed in detail in Section 3.1.

Cycles using one or more of several working fluids can be modeled using the CAESCAP code. This multiple working fluid capability is especially useful for combined cycle analysis. Working fluid capabilities include steam, air, nitrogen, and parahydrogen. The effect

of combustion products on air properties can also be modeled. The property libraries are described in Section 3.3.

The CAESCAP code has several features that greatly enhance its analysis capability. One of these features is an iteration capability. This allows the user to vary a parameter at one station to achieve a desired parameter value at another station. For example, cold side exit temperature may be varied to accomplish a specified heat exchanger effectiveness. The code iterates until the desired value is achieved. Another feature is helpful in performing parametric studies. When running repeat or sensitivity analyses, the user need only provide input for stations where changes are desired. If, for example, the effect of turbine efficiency on cycle heat rate were desired, the user need only add the one line of input for the new turbine efficiency for each repeat analysis. This procedure may be repeated for as many cases as desired and more than one component may be changed. Iteration and several other features are discussed in Section 3.2. The parametric analysis procedure is described in Appendix A.

The CAESCAP code is based on an Atomics International computer code (Hessler et al. 1964). It consists of a main program that reads cycle input, directs the cycle analysis by accessing component models and properties libraries in the form of subroutines, and calls other subroutines to do a performance analysis and provide the results as output. This organizational structure is shown schematically in Figure 2.1.

Cycles with up to 100 stations can be analyzed, with each station requiring usually one line of input. At each station the user must provide sufficient information such that the thermodynamic state is uniquely specified. Consider, for example, the simple gas turbine cycle shown in Figure 2.2. The input for Station 1 would be the air inlet conditions. The next line of input would be for Station 2 and would consist of a thermodynamic description of the compressor (e.g., isentropic efficiency and compression ratio). Together with the input for Station 1, this is sufficient information for the code to calculate

FIGURE 2.1 . The CAESCAP Code Organization

FIGURE 2.2. Simple Open Cycle Gas Turbine

the thermodynamic conditions at Station 2. Input for Stations 3 and 4 would describe the combustion and expansion processes, respectively. The code calculates the thermodynamic state at each station based on its input and the conditions calculated for the previous station.

When all station calculations have been completed, the code calculates the overall cycle efficiency. This is based on the accumulated power inputs and outputs of the cycle components. Several performance parameters are also calculated, including the generation heat rate and the round trip heat rate. These performance calculations are described in Section 3.4.

For output, the code first prints the user's inputs. This provides a check and a permanent record of inputs for future use. Next, the calculated working fluid conditions at each station are printed in tabular form. Included are the thermodynamic property values, flow rate, and energy transfer rates and efficiencies of the associated components. Then the operational parameters for major components (turbines, compressors, heat exchangers, and combustors) are summarized under each component category. Finally, the cycle performance parameters are printed.

Examples of input and output for several CAES cycle analyses are provided in Appendix B.

3.0 METHODOLOGY

This section describes the computational methodology used in the CAESCAP code. The models used to simulate cycle components are discussed first. Next, the analysis features and the properties library are described. Finally, the equations used to calculate performance parameters are summarized.

3.1 COMPONENT MODELS

The component models are included as subroutines in the CAESCAP code. Components are identified by a component identifier, **I**, included in each line of station input. These are used by subroutine MAIN to call the appropriate model subroutine when performing a cycle analysis. The identifiers and subroutines associated with each component model are listed in Table 3.1. The organization of these subroutines is shown in Figure 3.1. The component models are described in the following subsections.

TABLE 3.1. Model Component Identifiers and Subroutines

<u>Component</u>	<u>Identifier</u>	<u>Applicable Subroutines</u>
Turbine	2	TURB, STAGE, EDTDS, MACHC
Flow separator	3	DUCT
Heat exchanger	4	HEX
Phase separator	5	SEP
Pump	6	PUMP, EFFIC
Compressor	7	COMP, EFFIC
Combustor	12	CBUST
Fluid bed combustor	13	FBCOMB
Coal gasifier	14	GASSER

FIGURE 3.1. Component Model Subroutines

3.1.1 Turbines

Subroutine TURB is used to simulate an adiabatic axial flow turbine. The user may select either of two levels of modeling detail. The design model performs a detailed analysis of up to 24 stages with moisture control and bypass flow. However, if this level of detail is not required, the second model analyzes a simple single-stage expansion.

Design Model

In the design model, either the turbine output power or the inlet mass flow rate may be specified. The outlet pressure and shaft speed complete the required input. Stage loading is assumed to be equal; however, the user may specify loading for each stage. Other optional input for each stage includes specific speed-dependent moisture control effectiveness values and bypass flow fractions. Working fluid diverted by either moisture control or bypass flow may be included as inlet flow at any station in the cycle. However, note that the thermodynamic state will be assumed to be that of the flow to which it is added.

The turbine analysis is based on the similarity parameters specific speed, N_s , and specific diameter, D_s . They are used in subroutines EDTDS and MACHC to compute optimal geometries and maximum efficiencies. The use of these parameters is as described in Baljé (1962a). Subroutine STAGE is used to calculate the resulting thermodynamic changes through each stage. Finally, overall turbine efficiency and reheat factor are determined using an iterative process. Calculations begin with an efficiency estimate input by the user and an initial estimate of reheat factor provided by the code. These estimates are used in the stage calculations from which a new efficiency is calculated. This calculated efficiency is then used as the next estimate for another series of stage calculations. This procedure continues until the efficiency changes by less than 1%. Then the reheat factor is calculated. This calculated reheat factor replaces the initial estimate and stage calculations are repeated until the reheat factor also changes by less than 1%.

A detailed description of the turbine calculations is provided in Hessler et al. (1964).

Simple Turbine Model

When modeling a turbine as a simple, single-stage adiabatic expander, the required input is less detailed. The inlet state, exhaust pressure, and isentropic efficiency are the only inputs required. Using

the inlet conditions supplied by the previous station analysis and the exhaust pressure, the isentropic exit conditions are calculated. These are then corrected by the isentropic efficiency for the actual exit conditions.

Bypass flow and moisture control are not available with this option. Furthermore, the user does not have the option to specify turbine power output. This specific limitation may be overcome by using the iteration feature described in Section 3.2.4. Using the iteration feature, one of the parameters (e.g., exhaust pressure) is changed until the desired power output is achieved.

3.1.2 Pump

Subroutine **PUMP** is used to simulate a multistage pump. The design model can perform a detailed analysis of up to 20 stages. If this level of detail is not needed, the pump may be modeled as a simple single-stage pump.

Design Model

As in the turbine analysis, the design model pump analysis is based on the similarity parameters specific speed and specific diameter. Their use for pumps is described by Baljé (1962b). Input to this model consists of pressure rise per stage and shaft speed.

The analysis begins in subroutine **PUMP** with the calculation of specific speed based on shaft speed, volumetric flow rate and head rise. Then subroutine **EFFIC** is called for the specific diameter and efficiency of the stage being analyzed. Rotor diameter and power input complete the stage calculations. When all stages have been analyzed, the overall efficiency and outlet enthalpy are calculated.

Simple Pump Model

Inputs to the single-stage pump model include overall pressure rise and isentropic efficiency. The isentropic exit enthalpy is calculated using the inlet conditions and pressure rise. This is corrected with

the efficiency giving the actual outlet conditions from which the input power is calculated.

3.1.3 Compressor

Subroutine COMP is used to simulate a multistage compressor. The design model can perform a detailed analysis of up to 20 stages. Just as in the turbine and pump models, the user has the option of a simple single-stage compression when design calculations are not needed.

Design Model

The design model requires that the user specify the number of stages, the design shaft speed and the exhaust pressure. The code assumes equal pressure drops per stage. It then proceeds with the same equations as in the pump model to calculate efficiency, rotor diameter, and exit conditions.

Simple Compressor Model

The simple single-stage compression model requires that the user specify only the pressure rise and efficiency. The equations used to calculate thermodynamic exit conditions and power requirement are the same as those used for the simple single-stage pump model.

3.1.4 Heat Exchanger

Heat exchange devices are modeled using subroutine HEX. The model consists of an energy balance between the two flow streams in a counterflow heat exchanger. Heat transfer area is not calculated so the code contains no heat transfer models. Geometry is also not considered. Therefore, boilers, condensers, and heat exchangers can all be modeled using this subroutine. The model does include an effectiveness calculation, an approach temperature difference check, and a pinch point temperature calculation.

Because the cycle analysis follows the working fluid path, both sides of a heat exchanger are not analyzed consecutively. Consider a recuperator in a gas turbine cycle. After the cold side of the recuperator is analyzed, exit conditions from the combustor and turbine

will be required before the hot side can be analyzed. Because of this procedure, the subroutine contains two separate models, one for the first pass analysis and one for the second pass. Figure 3.2 will be used to illustrate these two options. The first side has inlet a and outlet b. Then the second pass has inlet c and outlet d. Heat transfer, Q , is shown in the positive direction.

FIGURE 3.2. Counterflow Heat Exchanger

First Pass Analysis

In the first pass analysis, the code calculates the pressure drop and rate of energy addition or removal for stream a-b and the exit conditions at b. User inputs specify pressure drop and energy transfer rate.

For pressure drop through this side of the heat exchanger, the user has the option of inputting either an absolute value, a percentage of total pressure, or the value of a constant multiplier to be used in calculating a flow rate-dependent pressure drop. In the latter case, pressure drop is calculated as

$$\Delta P = \left(\frac{\Delta P}{W^2} \right)_{\text{ref.}} W^2$$

where

$\left(\frac{\Delta P}{W^2} \right)_{\text{ref.}}$ is the constant multiplier

W is the flow rate through side a-b of the heat exchanger.

Three options are available for specifying energy transfer rate:

1. Energy transfer rate to stream a-b may be specified (positive or negative).
2. Exit temperature or enthalpy may be specified at Station b.
3. A temperature or enthalpy difference from a to b may be specified.

Second Pass Analysis

This option is used after the first pass analysis has been completed. Inputs include pressure drop and approach temperature difference. Pressure drop may be specified using any of the methods outlined in the first pass analysis description. The approach temperature difference is the minimum temperature difference allowed between streams at either end of the heat exchanger. For heat transfer as shown in Figure 3.2, this requirement states that

$$T_d - T_a \geq \Delta T_{\text{approach}}$$

and $T_c - T_b \geq \Delta T_{\text{approach}}$ *

Use of the approach temperature check ensures that realistic heat exchanger performance is maintained.

Because the first side of the heat exchanger has already been analyzed, the conditions at Stations a and b are known. Also the conditions at Station c are known and the exit conditions at Station d are needed. The rate of energy transfer to stream c-d is calculated from an energy balance

$$Q_d = W_b (H_b - H_a).$$

Enthalpy at d is then calculated as

$$H_d = H_c - Q_d/W_d.$$

Subroutine PROP is then called for the remaining properties.

Next, the code checks the ΔT approach between Stations a and d. If it is less than the user-specified minimum value, the temperature at Station b is changed and the cycle recalculated from that point. This iteration is continued until the approach temperature difference is satisfied between Stations a and d. Then the same check is made between temperatures at b and c. If not satisfied, the temperature at d is changed to obtain the desired value. With this new temperature a new energy transfer rate is found, thereby changing the temperature at b. Cycle calculation is begun again at Station b and both approach temperatures are checked. The process continues until both are satisfied. If not satisfied within several tries, an error message is printed.

Knowing the conditions at all four Stations a, b, c, and d, the heat exchanger effectiveness can now be calculated as follows:

$$\text{Effectiveness} = \frac{Q}{Q_{\max}} = \frac{C_h (T_{h1} - T_{h2})}{C_{\min} (T_{h1} - T_{c1})} = \frac{C_c (T_{c2} - T_{c1})}{C_{\min} (T_{h1} - T_{c1})}$$

where

$C_{\min}$ is the minimum value of (C_c , C_h)

and

$$C_c = W_c C_{pc}, \quad C_h = W_h C_{ph}$$

W_c = mass flow of coolant

C_{pc} = specific heat of coolant $\Delta H_c / \Delta T_c$

W_h = mass flow of hot substance

C_{ph} = specific heat of hot substance $\Delta H_h / \Delta T_h$.

After the cycle analysis is completed, subroutine POWER is called to print a summary of major components, including heat exchangers. At this time the code also calculates and prints the pinch point

temperature for each counterflow heat exchanger. The pinch point temperature is the minimum temperature difference occurring between the hot and cold fluid streams in a counterflow heat exchanger. This calculation is performed in subroutine PINCH.

Examples of inputs for heat exchangers are given throughout the user samples in Appendix B. Two are specifically worth noting. The first is that of a feedwater heater using two fluids in user sample 5. A method of achieving a desired heat exchanger effectiveness using the iteration station described in Section 3.2.4 is illustrated in user sample 2.

3.1.5 Phase Separator

A liquid-vapor separator is modeled in subroutine SEP. This subroutine models the separation of a saturated steam flow into a saturated vapor stream and a saturated liquid stream. Input consists of pressure drop and inlet and outlet station numbers. Pressure drop can be input using any of the options described in the heat exchanger section.

When using this component model the second exit stream station number must be defined. This is because only one outlet station is defined for each component. Definition of the second station is accomplished using the feature described in Section 3.2.2.

3.1.6 Flow Split, Mix or Throttle

Subroutine DUCT is used to simulate the splitting of a single flow or the combination of several flows. It may also be used to model the isenthalpic throttling of a single flow.

Flow Split

This option allows the user to split a flow into two, three, or four streams. For a two-way split, the user must specify one of the exit flow rates; then the other is calculated. For a four-way split, three of the outlet flow rates must be specified and the fourth is

calculated. More than four outlet streams may be specified by using successive flow split component models. The properties of the exit streams are assumed to be the same as those of the inlet flow.

When using the flow split option, only one outlet stream station number is defined. The remainder must be defined using the station definition feature described in Section 3.2.2. These inputs used to define the additional streams are also used to specify their mass flow rates as described above.

Flow Mix

With this option the code simulates the combination of up to four inlet streams, resulting in one outlet stream. The user need only specify the station numbers of the inlet and outlet streams. The pressure of the outlet flow is assumed to be the minimum of the inlet streams. The exit stream enthalpy is calculated as the mass flow weighted enthalpies of the inlet streams. For a combination of two streams .

$$H_{\text{exit}} = \frac{H_1 W_1 + H_2 W_2}{W_1 + W_2}$$

where 1 and 2 are inlet streams. Now that the enthalpy has been determined, subroutine PROP is called for the remaining exit flow properties.

Flow Throttle

This option is used to model an isenthalpic expansion. Other than the inlet and outlet station numbers, the only required input is pressure drop. It can be input using any of the methods described in Section 3.1.4.

3.1.7 Combustor

An air heating combustor is modeled in subroutine CBUST. This model was devised for Brayton cycle analysis. The user may choose one of three levels of modeling detail: a simple combustor for which only the rate of energy input is calculated; a fueled combustor where fuel

flow rate is calculated based on its higher heating value; or a "real" combustor where reactant constituents are used to calculate combustion product constituents and properties.

Simple Combustor

In this combustor model, the effect of a fuel stream on the exit flow rate and properties is not considered. The combustor process is simply modeled as the addition of sufficient energy per pound of inlet air to achieve the specified exit enthalpy or temperature. This calculated rate of energy input is corrected by a user-specified efficiency, E .

$$Q = (H_{\text{out}} - H_{\text{in}}) W/E$$

The mass flow and physical properties of the inlet air-flow are assumed to be unchanged over the combustor.

The required inputs for this option are exit temperature or enthalpy, pressure drop, and combustor efficiency.

Fueled Combustor

In this option, the effect of the fuel stream on exit mass flow is considered, but its effect on exit flow physical properties is not. The fuel stream is given a user-specified higher heating value, HHV, and an inlet enthalpy, H_f . Exiting flow rate from the combustor is calculated as the sum of the air and fuel flow rates. Exit enthalpy is calculated as

$$H_{\text{exit}} = (W_f \text{ HHV } E_c + W_f H_f + W_a H_a) / W_{\text{exit}}$$

where

E_c is the combustion efficiency

W_f, H_f is the mass flow rate and enthalpy of the fuel

W_a, H_a is the mass flow rate and enthalpy of the inlet air.

The code iterates on fuel mass flow rate until the exit temperature is within 2°F of the desired value.

Inputs required for this option are exit temperature, pressure drop, combustion efficiency, and fuel higher heating value and enthalpy. In addition, a fuel inlet station must be defined using the station definition feature of Section 3.2.2.

Real Combustor

For this option, the code includes the effect of combustion products on the exit flow physical properties. Composition of the exiting gases is calculated using the inlet air and fuel constituents. The code currently has capabilities for only one fuel, that resulting from the coal gasifier described in Section 3.1.9.

Initially the calculations in this model are the same as for the fueled combustor model. Exit mass flow is the sum of the inlet air and fuel mass flows. Exit enthalpy is calculated using the same equation. However, the fuel heating value, inlet enthalpy, and combustion temperature are no longer user-specified. The fuel higher heating value is fixed at 2295 Btu/lbm, the inlet enthalpy is previously determined at the gasifier outlet, and the combustion temperature is set at 1500°F. The calculation of the remaining exit properties is accomplished in a manner different from that of the fueled combustor model.

To simulate a real combustor, the model must incorporate the difference between combustion product and pure air properties. Because the CAESCAP code does not have combustion product properties, this is accomplished by correcting the calculated exit enthalpy by the ratio of combustion product to air specific heats. Using this corrected enthalpy, the remaining exit conditions are then found in the air properties subroutines. This procedure is discussed in detail in Section 3.3.2. As before, the code iterates on fuel flow rate until the 1500°F outlet temperature is reached.

At stations downstream of this combustor, gas composition and specific heat are recalculated and used to calculate station conditions. When modeling more than one combustor/turbine stage, the amount of oxygen available for combustion decreases with each stage. If there is insufficient oxygen for combustion, a message is printed and the analysis is terminated.

Because most of the component parameters are fixed for this option, the only user inputs are pressure drop and combustor efficiency.

3.1.8 Fluidized Bed Combustor

A fluidized bed combustion air heater is modeled in subroutine FBCOMB. The model describes an idealized tube/bed air flow with a constant temperature heat source. Based on user inputs, the code calculates size characteristics and outlet flow conditions.

User inputs include tube length, inside and outside tube radii, and heat transfer coefficients, tube thermal conductivity, bed depth, tube mass flow to tube area ratio, tube-side pressure drop, and bed-side combustion temperature. Subroutine FCOMB also has three options for specifying thermal performance:

- specified tube-side outlet temperature--Then the effectiveness, E, is calculated as

$$E = \frac{T_{te} - T_{ti}}{T_{be} - T_{ti}}$$

where

T_{te} is tube-side exit temperature

T_{ti} is the tube-side inlet temperature

T_{be} is the bed-side exit temperature.

- specified effectiveness--Then the tube-side exit temperature is calculated.
- Neither tube-side exit temperature nor effectiveness is specified; both are calculated.

For all options, the code then calculates the required heat transfer area from which the number of tubes can then be calculated.

Finally, the total energy transfer rate and fluid exit conditions are determined. In calculating the bed-side exit conditions, the code assumes a mass flow rate 31% of the tube-side value. Bed-side pressure drop is assumed to be 2% of the inlet pressure.

3.1.9 Coal Gasifier

Subroutine GASSER is used to simulate an entrained flow coal gasifier. The subroutine was written to specifically model a Foster Wheeler design. This moderate pressure, two-stage, air-blown unit was designed to produce low-Btu gas from coal for power generation.

The simulation uses the predicted performance values reported by Bissett (1978). These are summarized in Table 3.2. The model maintains an 80% coal gas efficiency. The effects of throughput are neglected, as is the effect of inlet pressure on fuel gas composition and higher heating value, HHV.

An air preheater must be used upstream of the gasifier to give a 900°F inlet air temperature. Coal inlet mass flow rate is calculated using an HHV of coal as 13,620 Btu/lbm. The product gas leaves the gasifier at 1700°F and has an HHV of 2295 Btu/lbm (150 Btu/scf). The mole fractions of the product gas constituents are given in Table 3.3.

Because most of the component parameters are fixed in the program, user input is limited to pressure drop.

3.2 ANALYSIS FEATURES

This section describes a number of CAESCAP features, some that perform necessary functions and others that enhance the overall cycle analysis capability. They are accessed by a line of input similar to that for a component model and they too are identified by the identifier ■. Most of these features are contained in subroutines; the rest are contained in the executive program, MAIN. The subroutines and their

TABLE 3.2. Predicted Performance Data for Foster Wheeler Gasifier

Coal composition, wt. %	
C	74.65
H	5.04
O	4.95
N	1.42
S	2.39
Ash	6.85
Moisture	4.70
Coal rate, lb/h	10,000
Steam/coal, lb/lb	0.324
Air/coal, lb/lb	3.697
Steam temperature, °F	900
Air temperature, °F	900
Gas composition, mole % (dry)	
CO	27.43
	3.39
H ₂	13.63
N ₂	53.38
CH ₄	1.78
	0.39
Gas yield, scf (dry)/lb coal	72.39
Materials per 1000 scf (CO + H ₂)	
Coal, lb	33.6
Air, scf	1636.1
Steam, lb	10.9
Carbon conversion, %	100

TABLE 3.3. Coal Gasifier Product Gas Constituents

<u>Constituent</u>	<u>Mole Fraction</u>	<u>Molecular Weight</u>
CO	0.2754	28.01
CO ₂	0.0340	44.01
H ₂	0.1368	2.016
N ₂	0.5359	28.016
CH ₄	0.0179	16.04
Product Gas Molecular Weight		24.787

associated identifiers are listed in Table 3.4. Their organization is shown in Figure 3.3. The first two of these features, working fluid and station definition, define new station numbers and are included in the cycle summary output. However, the last three--transfer, iteration, and accumulation--only manipulate data at existing stations and therefore are not included in the output.

TABLE 3.4. Analysis Feature Identifiers and Subroutines

<u>Feature</u>	<u>Identifier</u>	<u>Subroutines</u>
Station definition	1	MAIN
Working fluid definition	8	MAIN
Transfer	9	TRANS
Iteration	10	ITER
Accumulation	11	ACCUM

3.2.1 Working Fluid Definition

This feature is used to specify the type of working fluid and its conditions at the beginning of the cycle. **It** also defines the first station number. Therefore, **it** is the first line of station input in

FIGURE 3.3. Analysis Feature Subroutines

every cycle analysis. **It** must also be used again **if** the analysis reaches a part of the cycle where another working **f**luid is used (e.g., combined cycle analyses).

Input includes the thermodynamic conditions, type of working fluid and flow rate.

3.2.2 Station Definition

This feature is used to define sources and destinations of additional flows within the cycle. For example, **it** is used to define the destination of a stream from a phase separator or to specify the source of fuel for a combustor. These sources and destinations are given station numbers so that they may be referenced by the component models.

The use of the station definition feature is described in more detail in the component model descriptions with which **it** is used.

3.2.3 Transfer

This feature is used to duplicate all of one station's conditions at another station, **i.e.**, an equivalent station is defined. The only

input required for this feature is the station numbers of the donor and duplicate stations.

The logic for the transfer feature is contained in subroutine TRANS.

3.2.4 Iteration

The iteration feature is contained in subroutine ITER. **It** provides the capability of changing a property at one station until a desired property value at another station is achieved. This is a very useful feature and its potential use with several component models has already been suggested. See, for example, Section 3.1.4.

For a given station, the user must specify the property and property value desired, the station number and property to be varied to achieve the desired value, and the convergence limit to be satisfied. A list of property identifiers is given in Table 3.5. In the first iteration, the value to be changed is decreased by 10%. In subsequent iterations, a regula falsi procedure is used. **If** more than ten iterations are required, a warning message is printed and the analysis proceeds to the next station.

Examples of iteration usage are given throughout the user samples in Appendix B.

3.2.5 Accumulation

The logic for this feature is included in subroutine ACCUM. **It** provides the capability to select at a specified station any of the thermodynamic variables or component parameters, multiply **it** by a constant, and either substitute **it** for, or add **it** to, any of the variables at another specified station. This routine is designed to work properly within an iteration loop **if** the option is selected that subtracts previously added values before adding the current value.

TABLE 3.5. Property Identifiers for Use with the Iteration and Accumulation Features

<u>Identifier</u>	<u>Property</u>
1	Pressure (P)
2	Temperature (T)
3	Enthalpy (H)
4	Quality (X)
5	Flow rate (W)
6	Molecular Weight (F)
7	Efficiency (E) , or Effectiveness (E)
8	Speed (C)
9	Heat rate (Q)
10	Entropy (S)
11	Viscosity (A)
12	Specific volume (V)

3.3 PROPERTIES LIBRARY

Throughout the cycle analysis, the executive program, MAIN, and the component models call on the properties library for property values. The CAESCAP computer code has working fluid properties for steam, air, nitrogen, and parahydrogen. Combustion product properties are also available using a specific heat correction to the air properties. The properties library consists of numerous subroutines, most of them for steam properties. Subroutine PAN supplies property values for the remainder of the working fluids. Subroutine CPRAT calculates the ratios of specific heats used in modeling combustion product properties. Calls to any of these property subroutines are directed through subroutine PROP first. The organization of these subroutines is shown in Figure 3.4.

3.3.1 Steam Properties

Steam properties are determined using the 1967 ASME Steam Properties Library (Meyer et al. 1967; McClintock and Silvestri 1968). The following description is taken from Huber (1978).

FIGURE 3.4. Properties Subroutines

Tables 3.6 and 3.7 give the functions used to calculate thermodynamic and physical properties of water and steam, their arguments, and the temperature-pressure subregions in which they are applicable. The subregions are illustrated relative to the saturation line on the temperature-pressure diagram in Figure 3.5. Subregion 6 is the area just above and below the saturation line. When calculations of properties are needed near the critical point in Subregion 5, the accuracy of the functions used should be checked against the individual requirements because the properties vary rapidly in this area.

Many of the functions are interdependent. Consequently, if the use of a function is desired, the majority of the steam table functions must be loaded into computer memory.

The CAESCAP code initially calls for the following subroutines in the steam tables to initialize steam table constants: CCSR1, CCSR2, CCSR3, CCBLL, and COMALL. Then subroutine PROP calls the steam property function subroutines for required values.

TABLE 3.6. ASME Steam Table Single Valued Functions

State Unknown

(either wet (two-phase) or superheated)

<u>FORTTRAN</u> <u>Code Name</u>	<u>Function</u>	<u>Subregion</u>
HPS	$h = f(p,s)$	2, 3, 4
SPH	$s = f(p,h)$	2, 3
VPH	$v = f(p,h)$	2, 3
VPS	$v = f(p,s)$	2, 3, 4
TPH	$t = f(p,h)$	2, 3, 4
TPS	$t = f(p,s)$	2, 3, 4
THS	$t = f(h,s)$	2, 3, 4, 6
PHS	$p = f(h,s)$	2, 3, 4, 6
XPH	$x = f(p,h)$	
XPS	$x = f(p,s)$	

Superheated Steam

HPSD	$h = f(p,s)$	2, 3, 4
HPTD	$h = f(p,t)$	2, 3, 4
SPHD	$s = f(p,h)$	2, 3, 4
SPTD	$s = f(p,t)$	2, 3, 4
VPHD	$v = f(p,h)$	2, 3, 4
VPSD	$v = f(p,s)$	2, 3, 4
VPTD	$v = f(p,t)$	2, 3, 4
TSUPH/TPHD	$t = f(p,h)$	2
TSUPS/TPSD	$t = f(p,s)$	2, 3, 4
THSD	$t = f(h,s)$	2, 3, 4
PHSD	$p = f(h,s)$	2, 3, 4
VISV	$\mu = f(p,t)$	2, 3, 4
CONDV	$k = f(p,t)$	2, 3, 4
PRSTM	$Pr = f(p,t)$	2, 3, 4

Saturated Vapor

HGP	$h = f(p)$	Sat. line
HGT	$h = f(t)$	Sat. line
SGP	$s = f(p)$	Sat. line
SGT	$s = f(t)$	Sat. line
VGP	$v = f(p)$	Sat. line
VGT	$v = f(t)$	Sat. line
PSV	$p = f(s)$	Sat. line

Saturation Line and Wet Steam

<u>FORTTRAN</u> <u>Code Name</u>	<u>Function</u>	<u>Subregion</u>
HPSW	$h = f(p,s)$	6
SPHW	$s = f(p,h)$	6
VPHW	$v = f(p,h)$	6
VPSW	$v = f(p,s)$	6
TSL/TSATP	$t = f(p)$	Sat. line
PHSW	$p = f(h,s)$	6
PSL/PSATT	$p = f(t)$	Sat. line

Compressed Liquid

HPTL	$h = f(p,t)$	1, 3, 4
SPTL	$s = f(p,t)$	1, 3, 4
VPTL/VCL	$v = f(p,t)$	1, 3, 4
TPHL	$t = f(p,h)$	1, 4
TPSL	$t = f(p,s)$	1, 4
VISL	$\mu = f(p,t)$	1, 2, 3, 4
CONDL	$k = f(p,t)$	1
PRLIQ	$Pr = f(p,t)$	1

Saturated Liquid

TSLH	$t = f(h)$	Sat. line
HFP	$h = f(p)$	Sat. line
HFT/HSL	$h = f(t)$	Sat. line
SFP	$s = f(p)$	Sat. line
SFT/SSL	$s = f(t)$	Sat. line
VFP	$v = f(p)$	Sat. line
VFT/VSL	$v = f(t)$	Sat. line

NOTES:

Some subroutines have been given two names separated by a slash. When calling these subroutines, the names can be used interchangeably.

Symbols are defined as:

p = pressure, psia
h = specific enthalpy, Btu/lb
v = specific volume, ft³/lb
 μ = viscosity, lb/ft-sec
Pr = Prandtl number
Fc = critical flow, lb/hr-in²
°s = degrees superheat

t = temperature
s = specific entropy, Btu/lb-°F
x = quality by weight fraction, %/100
k = thermal conductivity, Btu/hr-ft-°F
Vc = critical velocity, ft/sec
 γ = isentropic exponent ($pv^\gamma = \text{constant}$)

TABLE 3.7. ASME Steam Table Multiple Valued Functions

<u>FORTTRAN Code Name</u>	<u>Function</u>	<u>State</u>
HSSISS	$h, t, v, x = f(p, s)$	Wet or superheated steam
HPSISS	$h, t, v, x = f(p, s)$	Superheated steam
HSS	$h, s, v = f(p, t)$	Superheated steam
HSV	$h, t, s, v = f(p)$	Saturated vapor
HCL	$h, s = f(p, t)$	Compressed liquid
HSSIQL	$h, t = f(p, s)$	Compressed liquid
SSSISS	$s, t, v, x = f(p, h)$	Wet or superheated steam
SPSISS	$s, t, v, x = f(p, h)$	Superheated steam
SSIQL	$s, t = f(p, h)$	Compressed liquid
CRFLO	$f_c, \text{ } ^\circ S = f(p, h)$	Wet or superheated steam
CRVEL	$V_c, \gamma = f(p, h)$	Wet or superheated steam
Isentropic Drop Subroutines		
ZSDT	$h_1, s_1, x_1, v_1, t_2, x_2, v_2, h_2$ $= f(p_1, p_2, t_1)$	Wet or superheated steam
ZSDH	$t_1, s_1, x_1, v_1, t_2, x_2, v_2, h_2$ $= f(p_1, p_2, h_1)$	Wet or superheated steam
ZSRT	$h_1, s_1, t_2, h_2 = f(p_1, p_2, t_1)$	Compressed liquid
ZSRH	$t_1, s_1, t_2, h_2 = f(p_1, p_2, h_1)$	Compressed liquid

NOTE:

Symbols are defined as:

p - pressure, psia

h - specific enthalpy, Btu/lb

v - specific volume ft³/lb

μ - viscosity, lb/ft-sec

Pr - Prandtl number

Fc - critical flow, lb/hr-in²

$^\circ S$ - degrees superheat

t - temperature

s - specific entropy, Btu/lb- $^\circ F$

x - quality by weight fraction, %/100

k - thermal conductivity, Btu/hr-ft- $^\circ F$

Vc - critical velocity, ft/sec

γ - isentropic exponent ($p v^\gamma = \text{constant}$)

FIGURE 3.5. Steam Table Subregions as a Function of Temperature and Pressure

3.3.2 Air, Nitrogen, and Parahydrogen Properties

The thermodynamic properties of air, nitrogen, and parahydrogen are calculated in subroutine PAN. The properties included are temperature, pressure, enthalpy, and availability. Subroutine PAN also models isentropic processes for these gases. Subroutine PAN is called by PROP with a calling index as the argument. Depending on the value of the calling index, subroutine PAN will perform one of four functions:

- If INDEX = 1, pressure and enthalpy are given; PAN will find temperature.

- If INDEX = 2, pressure and temperature are given; PAN will find enthalpy.
- If INDEX = 3, PAN finds the pressure, temperature, and enthalpy at the extremities of an isentropic process, given the pressure and enthalpy in, and the pressure out, of the isentropic process.
- If INDEX = 4, PAN finds the pressure, temperature, and enthalpy at the extremities of an isentropic process, given the pressure and enthalpy in, and enthalpy out, and given the efficiency to be applied.

In subroutine PAN, the method of solution for any of the above-mentioned cases typically involves an estimate of the desired property using a derived relationship (e.g., Ideal Gas Law). Subroutine PAN then uses this value in an iteration loop until a correct value is converged upon.

Combustion Product Properties

Consider the case of a mixture of combustion products undergoing a thermodynamic process. Because the qualities of the gas mixture (C_p , molecular weight) differ from those of air, behavior of the combustion gas mixture would be expected to differ from that of air through the same process. To analyze cycles that contain combustors or gasifiers, CAESCAP was modified to simulate these systems accurately.

To add the capability of using gas mixtures other than air, CAESCAP has been modified by the addition of subroutine CPRAT and by several changes in subroutine PAN. These changes were based on a method of approximating the behavior of the combustion products by the existing property routines for air. This is accomplished by relating the enthalpy change in a combustion product mixture to the enthalpy change in air by the ratio of their respective constant pressure specific heats, C_p . This is rationalized by the following argument.

Assume ideal gas behavior.

The enthalpy change in air -

$$\Delta H_{\text{air}} = C_{p \text{ air}} (T_{\text{in}} - T_{\text{exit}})$$

The enthalpy change for another gas mixture between the same temperatures -

$$\Delta H_{\text{mix}} = C_{p \text{ mix}} (T_{\text{in}} - T_{\text{exit}})$$

Dividing

$$\frac{\Delta H_{\text{mix}}}{\Delta H_{\text{air}}} = \frac{C_{p \text{ mix}}}{C_{p \text{ air}}}$$

Therefore,

$$\Delta H_{\text{mix}} = \frac{C_{p \text{ mix}}}{C_{p \text{ air}}} \Delta H_{\text{air}}$$

where $\frac{C_{p \text{ mix}}}{C_{p \text{ air}}}$ is referred to as the C_p ratio.

As an example of its use, consider the expansion of a combustion gas mixture through a turbine. First, the inlet enthalpy is corrected using the C_p ratio. This results in an equivalent air enthalpy, which provides an entry point for the air properties routine. An exit enthalpy for air is calculated following an isentropic path from the air inlet state. This exit enthalpy is then corrected using the C_p ratio to give the combustion product enthalpy.

This treatment of combustion products is used only in cycles with combustors using the fuel gas from the gasifier described in Section 3.1.9. Known fuel gas mole fractions are used to calculate combustion product mole fractions and molecular weights. These are, in turn, used to calculate the product gas specific heat and C_p ratio. This C_p ratio is then used as previously described for stations downstream of the combustor. In the summary output for the cycle, the C_p ratio is printed

in the quality column for these stations. Also, the molecular weight will be preceded by a minus sign. This is just a flag to the user that the gas is being simulated by air at those stations.

Combustion mixture properties calculated using specific heat correction have been compared to handbook values. The error in the calculated values increased with both higher temperatures and richer air/fuel mixtures. For most CAES cycles, temperatures are less than 1800°F and combustion involves greater than 400% excess air. For these limiting conditions, errors of 3% and 5% were observed for enthalpy and temperature, respectively. Enthalpy errors were consistently lower than those of temperature.

Availability Calculation

Availability, A , is defined as

$$A = -\Delta H + v_i \Delta P + T_d \Delta S$$

where A symbolizes the difference between the dead state (d) and the initial state (i).

From Van Wylen and Sonntag (1976),

$$T_d \Delta S = T_d \int_{T_i}^{T_d} \frac{C_{po}}{T} dT - T_d R \ln \left(\frac{P_d}{P_i} \right)$$

and

$$v_i \Delta P = -RT_i \left(1 - \frac{P_d}{P_i} \right).$$

Then the availability may be calculated as

$$A = -\Delta H - R T_i \left(1 - \frac{P_d}{P_i} \right) + T_d \int_{T_i}^{T_d} \frac{C_{po}}{T} dT - T_d R \ln \left(\frac{P_d}{P_i} \right)$$

or, using subscripts,

$$A = H_i - H_d - RT_i \left(1 - \frac{P_d}{P_i} \right) - T_d \int_{T_d}^{T_i} \frac{C_{po}}{T} dT + T_d R \ln \left(\frac{P_i}{P_d} \right)$$

This is the equation used to calculate availability in subroutine PAN. It requires integrated C_{po} equations. At this writing only those for air have been included so this calculation is limited to air cycles. The dead state used is 77°F (298.15°K) and 1 atm (101.32 kPa).

3.4 PERFORMANCE CALCULATIONS

When the code has finished calculating the thermodynamic conditions at each station, it calculates cycle performance parameters. These parameters are used to compare different CAES cycles or to observe the effects of variations on one cycle. These performance parameters and their equations are summarized below.

- Generation Heat Rate, HR_g

$$HR_g = \frac{Q_{tot}}{P_{out}}$$

- Charge Energy Factor, CEF

$$CEF = \frac{P_{out}}{P_{in}}$$

- Round Trip Heat Rate, HR_{rt}

$$HR_{rt} = HR_{gr} \frac{P_{gr}}{P_{out}} + HR_b \frac{P_b}{P_{out}} + HR_g$$

$$\text{where } HR_b = \frac{Q_b}{P_b}$$

For discontinuous cycles (all charging power comes from the grid), the above reduces to

$$HR_{rt} = \frac{HR_{gr}}{CEF} HR_g$$

where $HR_{gr} = 10,000 \text{ Btu/kWh}$

- Storage Efficiency, ESE

$$ESE = \frac{P_{out} - Q_{tot} \eta_{TH} / 3413 \text{ (Btu/kWh)}}{P_{in}}$$

where

P_{out} = the generator output power multiplied by an appropriate factor to account for plant auxiliaries during generation (kW)

P_{in} = the compression input power multiplied by an appropriate factor to account for plant auxiliaries during compression (kW)

P_b = compression power originating internally (kW)

P_{gr} = compression power from the grid (kW)

HR_{gr} = heat rate of the grid (Btu/kWh)

HR_b = heat rate associated with the CAES plant when no air is entering or leaving the storage reservoir (Btu/kWh)

Q_{tot} = energy input rate from combustors, coal gasifier, or fluid bed during generation (Btu/hr)

η_{TH} = thermal turbine efficiency.

In addition to these parameters, the input and output power, overall compression ratio and fuel use rate are also printed.

4.0 PROGRAM USAGE

The CAESCAP code is written in ASCII FORTRAN as used on the UNIVAC 1100/44 computer. When used on this computer, the Level 8R1 ASCII FORTRAN compiler should be selected. Use of compiler levels higher than 8R1 will require significant modification of the steam properties subroutines.

The CAESCAP code requires approximately 50,000 words of core memory on the UNIVAC computer. The computer time required for a cycle analysis depends on the number of stations and the number of iterations. Including input/output time and execution time, none of the analyses in Appendix B took more than 15 seconds. These fast run times make the CAESCAP code very economical to use. Each of the analyses in Appendix B cost less than one dollar to run.

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APPENDIX A
CAESCAP INPUT GUIDE

APPENDIX A

CAESCAP INPUT GUIDE

Input for CAESCAP is read from a data file by the executive program, MAIN. The input data file is divided into four groups:

1. title
2. program control - 1
3. station input
4. program control - 2.

Each of these four groups is described in the first section of this appendix. Station input for specific component models and analysis features is then described in the second section of this appendix.

The CAESCAP code features the option of nonrestrictive, list-directed data input or formatted input. The code will detect which option is being used. FORMAT statements are provided for the variables in each group. To further aid the user in setting up input files, several examples are given in Appendix B.

GENERAL INPUT DESCRIPTION

Group 1: Title

This is the first group in every input file. It consists of only one line of input.

```
READ    XTITLE (11), II = 1,20
FORMAT  20A4
```

XTITLE $\equiv$ a descriptive alphanumeric title.

Group 2: Program Control - 1

This first program control group consists of two lines of input.

```
READ    MAX, IP, IOPT1, IOPT2, EGEN, EMOT, EFBC, EQVB, EPLT
FORMAT  415, 5F5.3
```

MAX $\equiv$ the number of stations in the cycle, MAX $\leq$ 100

IP $\equiv$ an arbitrary cycle identification number

IOPTI $\equiv$ a debugging aid. IOPTI = 1, results are printed after each station calculation in addition to the summary listing at the completion of the cycle analysis. This option is useful because the program may abort prior to printing the summary listing. IOPTI = 0, results are not printed after each component calculation. Default, IOPTI = 0.

IOPT2 $\equiv$ performance calculation option. IOPT2 = 1, performance parameters are calculated and printed. Included are charge energy factor, storage efficiency, generation heat rate, and round trip heat rate. IOPT2 = 0, no performance parameters are calculated. Default, IOPT2 = 0.

EGEN $\equiv$ generator efficiency. Default, EGEN = 0.98.

EMOT $\equiv$ motor efficiency. Default, EMOT = 0.98.

EFBC $\equiv$ fluidized bed combustor efficiency. Default, EFBC = 0.98.

ECMB $\equiv$ combustor efficiency. Default, ECMB = 0.98.

EPLT $\equiv$ base plant efficiency. Default, EPLT = 1.0.

READ IV(II), II = 1, MAX
FORMAT 16I5

IV(II) $\equiv$ order of station calculation. IV(II) is the IIth station number in the cycle. Station numbers given to analysis features must also be included. The station number is specified as IT in each line of Group 3 input. If formatted input is selected, additional lines of input must be used for MAX > 16.

Group 3: Station Input

This group provides input to individual component models and analysis features. At least one line of input is required for every station; some component models require additional lines of input. The

variables as described here are for the general case. Their use for specific component models and analysis features is described in the following section.

```
READ    IT, I(IT), J(IT), K(IT), L(IT), M(IT), N(IT), P(IT),  
        T(IT), H(IT), X(IT), E(IT), C(IT), W(IT), LF(IT), Q(IT)  
FORMAT  7I5, 7F5.0, I5, F5.0
```

IT $\equiv$ the station number, $IT \leq 100$. The station number is arbitrary and need not follow sequentially from the previous station number.

I(IT) $\equiv$ component or analysis feature identifier

J(IT)→N(IT) $\equiv$ see specific component model or analysis feature description

P(IT) $\equiv$ station pressure, psia

T $\equiv$ station temperature, °F

H $\equiv$ station enthalpy, Btu/lbm

X $\equiv$ station quality, %/100

E $\equiv$ station efficiency, %/100

C $\equiv$ see specific component model or analysis feature description

W $\equiv$ station mass flow rate, lbm/sec

LF $\equiv$ working fluid identifier. LF(IT) = 1, fluid at station IT is air. LF(IT) = 2, fluid is nitrogen. LF(IT) = 3, fluid is parahydrogen. LF(IT) = 4, fluid is water.

Q $\equiv$ energy transfer rate, Btu/sec

```
READ    F1, F2, F3, ... FN  
FORMAT  16F5.0
```

F1→FN $\equiv$ component-dependent variables; see individual component descriptions.

Group 4: Program Control - 2

This second program control group allows the user to choose among several courses of action after the initial cycle analysis has been performed. The user may terminate program execution or perform another cycle analysis. In the latter case, input Groups 1 through 3 must follow for the next cycle analysis. A third option is useful for performing sensitivity studies of a component parameter in the preceding cycle. This option allows the user to change one or more lines in the preceding Group 3 input and rerun the cycle analysis. Group 4 inputs may be repeated.

```
READ    N(II), II = 1, MAX
FORMAT  8011
```

$N(II) \equiv$ the control variable for station number II . $N(II) = 1$, read in a new line of input for station II and use the new parameters in all subsequent sensitivity runs (if Group 4 is repeated). An additional line of input must be used if $MAX > 80$. $N(II) = 2$, read in a new line of input for station II and use the new parameters for this sensitivity run only. $N(1) = 3$, i.e., a 3 in column 1, read in Groups 1 through 3 for a new cycle analysis case. $N(1) = 4$, terminate program execution.

$MAX1 \equiv$ the maximum station number, $MAX1 < 100$.

The following line of input is required for each occurrence of $N = 1$ or 2. When inputs for more than one station are to be changed, the lines of input must be in the order of calculation.

```
READ    IT, I(IT), J(IT), K(IT), L(IT), M(IT), N(IT), P(IT), T(IT),
        H(IT), X(IT), E(IT), C(IT), W(IT), LF(IT), Q(IT)
FORMAT  715, 7F5.0, I5, F5.0
```

$IT \equiv$ station number for which new parameters are being input.

$I(IT) \rightarrow Q(IT) \equiv$ new parameters at station IT as defined in Group 3.

COMPONENT MODEL AND ANALYSIS FEATURE INPUTS

The station inputs introduced in the preceding section of this appendix are described here for specific component models and analysis features. Component model inputs are discussed first, followed by analysis feature inputs. The common READ and FORMAT statements are reprinted for reference.

```
READ    IT, I(IT), J(IT), K(IT), L(IT), M(IT), N(IT), P(IT), T(IT),  
        H(IT), X(IT), E(IT), C(IT), W(IT), LF(IT), Q(IT)  
FORMAT  715, 7F5.0 I5, F5.0
```

Turbine

The following are inputs to the model described in Section 3.1.1 of the main text of this report.

- IT ≡ the station number at the turbine exhaust
- I(IT) ≡ component identifier; I(IT) = 2 for a turbine
- J(IT) ≡ station to which bypass flow is directed. Let J(IT) = IT for no moisture bypass. Leave blank for simple turbine model.
- K(IT) ≡ pressure drop option. K(IT) = 1, P(IT) is the absolute pressure at station IT. K(IT) = 2, P(IT) is the pressure drop over the turbine; i.e., $P(M(IT)) - P(IT)$. K(IT) = 3, P(IT) is the ratio of inlet to outlet pressure, i.e., $P(M(IT))/P(IT)$.
- L(IT) ≡ analysis option. L(IT) = 0, simple turbine model. L(IT) = 1, design model, specify power output, Q(IT), and flow rate will be calculated. L(IT) = 2, specify flow rate, W(IT), and power output will be calculated. Default, L(IT) = 0.
- M(IT) ≡ turbine inlet station number
- N(IT) ≡ number of turbine stages, N(IT) ≤ 24. Leave blank for simple turbine model.
- P(IT) ≡ turbine exhaust pressure, according to K(IT), psia

T(IT),H(IT),

X(IT) $\equiv$ not used, leave blank

E(IT) $\equiv$ turbine efficiency, estimate for L(IT) = 1 or 2, specify
for L(IT) = 0. Default, E(IT) = 0.85.

C(IT) $\equiv$ turbine shaft speed, rpm. Specify only for L(IT) = 1,2.

W(IT) $\equiv$ turbine mass flow, lbm/sec. Specify only for L(IT) = 2.

LF(IT) $\equiv$ not used, leave blank

Q(IT) $\equiv$ turbine power output, Btu/sec. Specify only for
L(IT) = 1.

Six additional lines of input are required for L(IT) = 1 or 2,
i.e., the design option.

READ EMCE1 (II, JJ), JJ = 1, N(IT)

FORMAT 16F5.3

EMCE1(II,JJ) $\equiv$ moisture control effectiveness for stage JJ of turbine
II, for specific speed ≤ 30 , for each stage

READ EMCE2 (II, JJ), JJ = 1, N(IT)

FORMAT 16F5.3

EMCE2(II,JJ) $\equiv$ moisture control effectiveness for specific speed > 30 ,
for each stage

READ PCBYP (II, JJ), JJ = 1, N(IT)

FORMAT 16F5.3

PCBYP(II,JJ) $\equiv$ bypass fraction; enter as fraction of first stage flow
rate for each stage

READ WTBYP (II, JJ), JJ = 1, N(IT)

FORMAT 16F5.3

WTBYP(II,JJ) $\equiv$ flow rate of bypass in lbm/sec; specified for each stage

READ PRS (II, JJ), JJ = 1, N(IT)

FORMAT 16F5.3

PRS(II,JJ) $\equiv$ pressure ratio for each stage. Sum of PRS must equal
unity for a given turbine.

```
READ  EC (II, JJ), JJ = 1, N(IT)
FORMAT 16F5.3
```

EC(II,JJ) $\equiv$ enthalpy ratio for each stage.

Pump

The following are inputs to the model described in Section 3.1.2 of the main text.

IT $\equiv$ the station number at the pump exit

I(IT) $\equiv$ component identifier; I(IT) = 6 for a pump

J(IT),K(IT),
L(IT) $\equiv$ not used, leave blank

M(IT) $\equiv$ pump inlet station number

N(IT) $\equiv$ number of stages, N(IT) ≤ 20 . N(IT) = 1, simple pump model is assumed. N(IT) >1, number of stages to be used for design calculations. Default, N(IT) = 1.

P(IT) $\equiv$ exit pressure, psia

T(IT),H(IT),
X(IT) $\equiv$ not used, leave blank

E(IT) $\equiv$ pump efficiency. Specify for N(IT) = 1. Default, E(IT) = 0.50. Leave blank for N(IT) >1; it will be calculated.

C(IT) $\equiv$ pump shaft speed, rpm. Input only for N(IT) >1.

W(IT),LF(IT),
Q(IT) $\equiv$ not used, leave blank.

An additional line of input is required for N >1.

```
READ  DELP (II,JJ), JJ = N(IT)
FORMAT 16F5.0
```

DELP(II,JJ) $\equiv$ pressure rise for stage JJ.

Compressor

The following are inputs to the model described in Section 3.1.3.

IT $\equiv$ the station number at the compressor outlet

I(IT) $\equiv$ component identifier; I(IT) = 7 for a compressor

J(IT) $\equiv$ not used, leave blank

K(IT) $\equiv$ pressure drop option. K(IT) = 1, P(IT) is the absolute pressure at station IT. K(IT) = 2, P(IT) is the pressure rise over the compressor, i.e., $P(IT) - P(M(IT))$. K(IT) = 3, P(IT) is the ratio of outlet to inlet pressure, i.e., $P(IT)/P(M(IT))$.

L(IT) $\equiv$ not used, leave blank

M(IT) $\equiv$ pump inlet station number

N(IT) $\equiv$ number of compressor stages, N(IT) ≤ 20 . If N(IT) = 1, simple compressor model is used. For N(IT) > 1, design calculations are performed.

P(IT) $\equiv$ compressor exhaust pressure, according to K(IT), psia

T(IT), H(IT),

X(IT) $\equiv$ not used, leave blank

E(IT) $\equiv$ compressor isentropic efficiency. Specify for N(IT) = 1. Default, E(IT) = 0.85. Leave blank for N(IT) > 1.

C(IT) $\equiv$ compressor shaft speed, rpm. Input only for N(IT) > 1.

W(IT), LF(IT),

Q(IT) $\equiv$ not used, leave blank.

Heat Exchanger

The following are inputs to the model described in Section 3.1.4.

IT $\equiv$ the station number at the heat exchanger exit

I(IT) $\equiv$ component identifier; I(IT) = 4 for a heat exchanger-

J(IT) $\equiv$ inlet station number for first pass; specify for L(IT) = 4 only

$K(IT)$ $\equiv$ outlet station number for first pass; specify for
 $L(IT) = 4$ only

$L(IT)$ $\equiv$ analysis option. $L(IT) = 1$, specify $Q(IT)$, the rate of energy transfer to (+) or loss from (-) the working fluid, on the first or only pass through a heat exchanger. $L(IT) = 2$, specify working fluid outlet temperature or enthalpy on the first or only pass through a heat exchanger. $L(IT) = 3$, specify temperature change ($T(IT) = \Delta T$) or enthalpy change ($H(IT) = \Delta H$) as positive or negative over the first or only pass through a heat exchanger. $L(IT) = 4$, this is the second pass analysis; i.e., the first pass has been previously analyzed. Specify only the approach temperature difference in $E(IT)$ for $L(IT) = 4$.

$M(IT)$ $\equiv$ heat exchanger inlet station number for the side being analyzed

$N(IT)$ $\equiv$ pressure drop option. $N(IT) = 1$, $P(IT)$ is the absolute pressure at the exit station, IT . $N(IT) = 2$, $P(IT)$ is the pressure drop over the side of the heat exchanger being analyzed; i.e., $P(M(IT)) - P(IT)$. $N(IT) = 3$, $P(IT)$ is the pressure drop expressed as a fraction of the inlet pressure, $P(M(IT))$. $N(IT) = 4$, specify the value of the constant multiplier, $(\Delta P/W^2)_{ref}$, in $C(IT)$.

$P(IT)$ $\equiv$ pressure drop according to $N(IT)$, psia

$T(IT)$ $\equiv$ exit temperature or temperature change according to
 $L(IT)$, °F

$H(IT)$ $\equiv$ exit enthalpy or enthalpy change according to $L(IT)$,
Btu/lbm

$X(IT)$ $\equiv$ not used, leave blank

$E(IT)$ $\equiv$ approach temperature difference, °F. Specify only for
 $L(IT) = 4$.

$C(IT)$ $\equiv$ value of the constant multiplier, $(\Delta P/W^2)_{ref}$. Specify only for $N(IT) = 4$.

$W(IT), LF(IT)$ $\equiv$ not used, leave blank

$Q(IT)$ $\equiv$ energy transfer rate, Btu/sec. Specify only for $L(IT) = 1$.

Phase Separator

The following are inputs to the model described in Section 3.1.5.

IT $\equiv$ the station number at the outlet for the separated liquid stream

$I(IT)$ $\equiv$ component identifier; $I(IT) = 5$ for a phase separator

$J(IT)$ $\equiv$ station number of the outlet for the separated vapor stream. This station must be defined on the next line of input.

$K(IT), L(IT)$ $\equiv$ not used, leave blank

$M(IT)$ $\equiv$ inlet station number of the saturated mixture

$N(IT)$ $\equiv$ not used, leave blank

$P(IT)$ $\equiv$ pressure drop, psia

$T(IT), H(IT),$
 $X(IT), E(IT)$ $\equiv$ not used, leave blank

$C(IT)$ $\equiv$ value of the constant multiplier, $(\Delta P/W^2)_{ref}$. This may be specified rather than $P(IT)$.

$W(IT), LF(IT),$
 $Q(IT)$ $\equiv$ not used, leave blank.

Flow Split, Mix or Throttle

The following are inputs to the model described in Section 3.1.6.

IT $\equiv$ the station number; specific locations are discussed under Flow Configurations and Mass Flow Options (to follow).

$I(IT)$ $\equiv$ component identifier; $I(IT) = 3$ for a flow split, mix or throttle

$J(IT)$ $\equiv$ analysis option. $J(IT) = 1$, flow split. $J(IT) = 2$, flow mix. $J(IT) = 3$, flow throttle. Possible flow configurations for each of these options are discussed below.

$K(IT), L(IT)$ $\equiv$ station numbers; see discussion below for locations

$M(IT)$ $\equiv$ station number; see discussion below for location

$N(IT)$ $\equiv$ station number; see discussion below for location

$P(IT)$ $\equiv$ pressure drop, psia. If $P(IT)$ is positive and greater than 1, it is assumed to be the pressure drop ΔP . If positive and less than 1, that fraction of the inlet pressure, $P(M(IT))$, is assumed to be the pressure drop. If negative, it is assumed to be the exit pressure $P(IT)$. Specify only for $J(IT) = 3$.

$T(IT), H(IT),$
 $X(IT), E(IT)$ $\equiv$ not used, leave blank

$C(IT)$ $\equiv$ value of the constant multiplier, $(\Delta P/W^2)_{ref}$.

$W(IT)$ $\equiv$ mass flow rate, lbm/sec, used only for $J(IT) = 1$. See discussion of mass flow options below.

$LF(IT), Q(IT)$ $\equiv$ not used, leave blank.

Flow Configurations and Mass Flow Options

For $J(IT) = 1$:

2-Way Split

Specify $W(IT)$ as negative for lbm/sec split to $K(IT)$; specify $W(IT)$ as positive for a fraction of inlet flow split to IT .

3-Way Split

$W(IT)$ is specified as the fraction of inlet flow split to station IT . The fraction of flow going to station $L(IT)$ must be specified on the next line of input using the station definition feature.

4-Way Split

$W(IT)$ is specified as the fraction of inlet flow split to station IT . The fraction of flow going to stations $L(IT)$ and $N(IT)$ must be specified on the next two lines of input using the station definition feature.

For $J(IT) = 2$, label designations are analogous to those for $J(IT) = 1$, except that IT and $M(IT)$ are switched. $K(IT)$, $L(IT)$, and $N(IT)$ become inlet stream station numbers. $W(IT)$ is left blank because it is only the sum of the entering flows.

For $J(IT) = 3$, only $P(IT)$ and $M(IT)$ need be specified.

Air Heating Combustor

The following are inputs to the model described in Section 3.1.7.

$IT \equiv$ the station number at the combustor outlet

$I(IT) \equiv$ component identifier; $I(IT) = 12$ for a combustor

$J(IT) \equiv$ the station number of the line of input that contains the fuel heating value. The line of input is in the form of a station definition with the heating value in Btu/lbm

located in the X column. This line is usually located at the end of the Group 3 input. Specify only for $L(IT) = 2$.

$K(IT)$ $\equiv$ pressure drop option. $K(IT) = 1$, $P(IT)$ is the absolute pressure at the exit station, IT. $K(IT) = 2$, $P(IT)$ is the pressure drop. $K(IT) = 3$, $P(IT)$ is the pressure drop expressed as a fraction of the inlet pressure, $P(M(IT))$.

$L(IT)$ $\equiv$ analysis option. $L(IT) = 1$, simple combustor analysis. $L(IT) = 2$, fueled combustor analysis. $L(IT) = 3$, real combustor analysis.

$M(IT)$ $\equiv$ air inlet station number

$N(IT)$ $\equiv$ station number of the fuel source. Specify only for $L(IT) = 2$ or 3. For $L(IT) = 2$, the station must be defined on the next line of input; included should be the fuel inlet enthalpy in Btu/lbm. For $L(IT) = 3$, the fuel source and enthalpy are determined in the gasifier analysis.

$P(IT)$ $\equiv$ pressure drop according to $K(IT)$, psia

$T(IT)$ $\equiv$ outlet air temperature, °F. Specify only for $L(IT) = 1$ or 2.

$H(IT)$ $\equiv$ outlet air enthalpy, Btu/lbm. This may be specified rather than $T(IT)$ for $L(IT) = 1$ only. Leave blank for $L(IT) = 2$ or 3.

$X(IT)$ $\equiv$ not used, leave blank

$E(IT)$ $\equiv$ combustor efficiency. Default, $E(IT) = 0.98$.

$C(IT), W(IT),$
 $LF(IT), Q(IT)$ $\equiv$ not used, leave blank.

Fluidized Bed Combustor

The following are inputs to the model described in Section 3.1.8.

IT $\equiv$ the station number at the tube-side outlet

$I(IT)$ $\equiv$ component identifier; $I(IT) = 13$ for a fluidized bed combustor

$J(IT)$ $\equiv$ input option. $J(IT) = 0$, use default values of design parameters. $J(IT) = 1$, input design parameters described below.

$K(IT)$ $\equiv$ pressure drop option. $K(IT) = 1$, $P(IT)$ is the absolute pressure at the exit station, IT . $K(IT) = 2$, $P(IT)$ is the pressure drop. $K(IT) = 3$, $P(IT)$ is the tube-side pressure drop expressed as a fraction of the inlet pressure, $P(M(IT))$.

$L(IT)$ $\equiv$ bed-side inlet station number

$M(IT)$ $\equiv$ tube-side inlet station number

$N(IT)$ $\equiv$ bed-side outlet station number

$P(IT)$ $\equiv$ tube-side pressure drop according to $K(IT)$, psia

$T(IT)$ $\equiv$ tube-side outlet temperature, °F. If $T(IT)$ is specified, effectiveness, $E(IT)$, will be calculated. If $T(IT)$ is not specified, but $E(IT)$ is, $T(IT)$ will be calculated. If neither $T(IT)$ nor $E(IT)$ is specified, both will be calculated.

$H(IT), X(IT)$ $\equiv$ not used, leave blank

$E(IT)$ $\equiv$ effectiveness, %/100

$C(IT), W(IT),$
 $LF(IT), Q(IT)$ $\equiv$ not used, leave blank.

One additional line of input is required for $J(IT) = 1$. If any of the fields are left blank, default values are assumed.

READ TBED, R0, R1, XL, HTO, HTI, HBED, TTC, AMASS, STMFL, XTUB
FORMAT 16F5.3

TBED $\equiv$ fluidized bed temperature, °F. Default, TBED = 1650°F.

R0 $\equiv$ tube outside radius, in. Default, R0 = 0.25 in.

R1 $\equiv$ tube inside radius, in. Default, R1 = 0.18 in.

$XL \equiv$ immersed tube length, ft. Default, $XL = 5.6$ ft.
 $HTO \equiv$ outside tube heat transfer coefficient, Btu/hr'ft².
 Default, $HTO = 50.0$ Btu/hr'ft².
 $HTI \equiv$ inside tube heat transfer coefficient, Btu/hr'ft².
 Default, $HTI = 97.6$ Btu/hr'ft².
 $HBED \equiv$ immersed bed depth, ft. Default, $HBED = 4$ ft.
 $TTC \equiv$ tube thermal conductivity. Default, $TTC = 25$ Btu/hr'ft.
 $AMASS \equiv$ tube mass flow/tube area ratio, lbm/sec'ft². Default,
 $AMASS = 22.9$ lbm/sec'ft²
 $STMFL \equiv$ single tube mass flow, lbm/sec. Default, $STMFL =$ tube
 flow area x $AMASS$
 $XTUB \equiv$ total number of tubes in the bed. Default, $XTUB =$
 $W(IT)/STMFL*1.1$.

Entrained Flow Coal Gasifier

The following are inputs to the model described in Section 3.1.9.

$IT \equiv$ the station number at the gasifier outlet
 $I(IT) \equiv$ component identifier; $I(IT) = 14$ for a gasifier
 $J(IT) \equiv$ station number of the fuel source. The station must be
 defined on the next line of input using the station
 definition feature. Only the station number should be
 specified because the fuel properties are fixed for this
 model.
 $K(IT) \equiv$ pressure drop option. $K(IT) = 1$, $P(IT)$ is the absolute
 pressure at the exit station, IT . $K(IT) = 2$, $P(IT)$ is
 the pressure drop over the gasifier. $K(IT) = 3$, $P(IT)$ is
 the pressure drop expressed as a fraction of the inlet
 pressure, $P(M(IT))$.
 $L(IT) \equiv$ not used, leave blank
 $M(IT) \equiv$ inlet air station number
 $N(IT) \rightarrow Q(IT) \equiv$ not used, leave blank.

Working Fluid Definition

The following are inputs to the analysis feature described in Section 3.2.1.

IT $\equiv$ the station number

I(IT) $\equiv$ the analysis feature identifier, I(IT) = 8

J(IT),K(IT),
L(IT),M(IT),

N(IT) $\equiv$ not used, leave blank

P(IT) $\equiv$ pressure at station IT, psia

T(IT) $\equiv$ temperature at station IT, °F

H(IT) $\equiv$ enthalpy at station IT, Btu/lbm. H(IT) may be specified rather than T(IT), but not both.

X(IT) $\equiv$ quality, %/100. Specify only for LF(IT) = 4.

E(IT),C(IT) $\equiv$ not used, leave blank

W(IT) $\equiv$ mass flow rate at station IT, lbm/sec

LF(IT) $\equiv$ working fluid identifier. LF(IT) = 1, fluid at station IT is air. LF(IT) = 2, fluid is nitrogen. LF(IT) = 3, fluid is parahydrogen. LF(IT) = 4, fluid is water.

Q(IT) $\equiv$ not used, leave blank.

Station Definition

The following are inputs to the analysis feature described in Section 3.2.2.

IT $\equiv$ the station number being defined

I(IT) $\equiv$ the analysis feature identifier, I(IT) = 1

J(IT),K(IT),
L(IT),M(IT),

N(IT) $\equiv$ not used, leave blank

P(IT),T(IT),
H(IT),X(IT),
E(IT),C(IT),
W(IT),LF(IT),

Q(IT) $\equiv$ see specific application.

Transfer

The following are inputs to the analysis feature described in Section 3.2.3.

$IT \equiv$ the station number to which properties will be transferred

$I(IT) \equiv$ the analysis feature identifier, $I(IT) = 9$

$J(IT), K(IT),$
 $L(IT) \equiv$ not used, leave blank

$M(IT) \equiv$ station number from which all properties are to be transferred to station IT

$N(IT) \rightarrow Q(IT) \equiv$ not used, leave blank.

Iteration

The following are inputs to the analysis feature described in Section 3.2.4.

$IT \equiv$ the station number

$I(IT) \equiv$ the analysis feature identifier, $I(IT) = 10$

$J(IT) \equiv$ identifier of property to have value $C(IT)$ at station $M(IT)$. A list of property identifiers is given in Table A.1.

$K(IT) \equiv$ station at which property $L(IT)$ is to be changed. If station $K(IT)$ is a flow split or throttle, let $K(IT) = K(IT) + MAX1$, where $MAX1$ is the maximum station number.

$L(IT) \equiv$ identifier of property to be changed at station $K(IT)$ to accomplish the desired value at station $M(IT)$

$M(IT) \equiv$ station number at which the specified property value is desired

$N(IT) \equiv$ station number at which to begin the iteration. Stations $N(IT)$ through IT will be recalculated for each iteration.

TABLE A.1. Property Identifiers for Use with the Iteration and Accumulation Features

<u>Identifier</u>	<u>Property</u>
1	Pressure (P)
2	Temperature (T)
3	Enthalpy (H)
4	Quality (X)
5	Flow rate (W)
6	Molecular weight (F)
7	Efficiency (E), or Effectiveness (E)
8	Speed (C)
9	Heat rate (Q)
10	Entropy (S)
11	Viscosity (A)
12	Specific volume (V)

$P(IT), T(IT),$

$H(IT) \equiv$ not used, leave blank

$X(IT) \equiv$ convergence criterion, %/100

$E(IT) \equiv$ not used, leave blank

$C(IT) \equiv$ the desired value of property $J(IT)$ at station $M(IT)$

$W(IT), LF(IT),$

$Q(IT) \equiv$ not used, leave blank.

Accumulation

The following are inputs to the analysis feature described in Section 3.2.5.

$IT \equiv$ the station number

$I(IT) \equiv$ the analysis feature identifier, $I(IT) = 11$

$J(IT) \equiv$ identifier of property to be placed at station $K(IT)$ according to $N(IT)$. A list of property identifiers is given in Table A.1.

$K(IT) \equiv$ receiving station number

$L(IT)$ $\equiv$ identifier of property to be picked up at station $M(IT)$

$M(IT)$ $\square$ donor station number

$N(IT)$ $\equiv$ analysis option. $N(IT) = 1$, replace the specified property value at $K(IT)$ with the specified property value at $M(IT)$. $N(IT) = 2$, add the specified property value at $K(IT)$ to the specified property value at $M(IT)$ after subtracting the value previously added (useful when station IT falls inside an iteration loop). $N(IT) = 3$, add the specified property value at $K(IT)$ to the specified property value at $M(IT)$, without subtracting the previous value.

$P(IT), T(IT),$
 $H(IT), X(IT),$

$E(IT)$ $\equiv$ not used, leave blank

$C(IT)$ $\equiv$ fraction of property value to be picked up at $M(IT)$.

Default, $C(IT) = 1.0$.

$W(IT), LF(IT),$

$Q(IT)$ $\equiv$ not used, leave blank.

APPENDIX B

USER SAMPLES

APPENDIX B

USER SAMPLES

This appendix describes inputs to the CAESCAP code and the resulting output for analyses of five typical CAES cycles. The CAES cycles analyzed were:

- conventional CAES
- adiabatic CAES
- hybrid CAES
- PFBC CAES
- direct coupled steam-CAES

The code inputs were based on published reports describing each cycle. An attempt was made to match reported conditions and in most cases this was accomplished. Discrepancies and necessary assumptions are noted.

Performance calculations were made for each cycle and the results are presented in Table B.1. The equations used are described in Section 3.4 of the main text. A motor and generator efficiency of 0.98 was used. Turbine power was charged for plant auxiliaries as follows:

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

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

USER SAMPLE 1 - CONVENTIONAL CAES

This cycle analysis was based on the conceptual design performed by Acres American, Inc. (1981b). The cycle diagram is shown in Figure B.1. Of the two alternative turbine arrangements described in the 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.

TABLE 6.1. Cycle Performance Parameters

Cycle	Charge Energy Factor	Generation Heat Rate (Btu/kW hr)	Round Trip Heat Rate (Btu/kW hr)
Conventional	1.35	3960	11375
Adiabatic	0.66	0	15200
Hybrid	1.03	2820	12500
PFBC	1.08	4220	13500
Direct coupled steam (a)	1.44	3460	14200 ^(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 TES input was apparently left out.

FIGURE B.1. Conventional CAES Cycle Diagram

The input for this cycle analysis is shown in Figure B.2. List directed input was used in this case. Station numbers correspond to those given in Figure B.1. The resulting output is presented in Figures B.3, B.4, and B.5. Figure B.3 shows the listing of station conditions. Figure B.4 shows the component performance summary. Figure B.5 illustrates the summary of performance parameters that result from setting IOPT2 = 1 in the Group 2 input.

```

1      CONVENTIONAL CAES
2      28,0,1,1/
3      1,2,30,3,4,31,5,6,32,7,8,33,9,10,34,11,12,13,14,15,25,16,17,26,18,36,19,50/
4      1,8,.,.,.,14,7,59,.,.,.,661,.,1/
5      2,7,.,1,.,1,95,4/
6      30,10,2,2,7,2,2,.,.,.,001,.,504,/
7      3,4,.,2,2,3,.,01,120,/
8      4,7,.,1,.,3,.,174,/
9      31,10,2,4,7,4,4,.,.,.,001,.,257,/
10     5,4,.,2,4,3,.,01,120,/
11     6,7,.,1,.,5,.,294,/
12     32,10,2,6,7,6,6,.,.,.,001,.,237,/
13     7,4,.,2,6,3,.,01,120,/
14     8,7,.,1,.,7,.,567,/
15     33,10,2,8,7,8,8,.,.,.,001,.,273,/
16     9,4,.,2,8,3,.,01,120,/
17     10,7,.,1,.,9,.,1015,/
18     34,10,2,10,7,10,10,.,.,.,001,.,248,/
19     11,4,.,2,10,3,.,01,140,/
20     12,3,3,.,11,.,-950,/
21     13,4,.,2,12,1,921,.,680,/
22     14,3,3,.,13,.,-841,/
23     15,12,50,2,2,14,25,29,.,1022,.,.,1.0/
24     25,1,.,.,.,.,150,/
25     16,2,.,1,.,15,.,160,.,.,.,86/
26     17,17,50,2,2,16,26,0,0,1652,.,.,1.0/
27     26,1,.,.,.,.,150,/
28     18,2,.,1,.,17,.,15,1/
29     36,10,2,18,7,18,18,.,.,.,001,.,824,/
30     19,4,12,13,4,18,1,14,7,.,.,1.0/
31     50,1,.,.,.,.,18057,/
32     4

```

FIGURE B.2. Inputs for Conventional CAES Cycle Analysis

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 BTU/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	39.77	.0000	28.966	661.000	71418.27	.81
3	94.446	138.16	120.00	.0000	35.15	.0000	28.966	661.000	-62000.48	.00
4	174.000	171.14	256.98	.0000	51.55	.0000	28.966	661.000	21795.07	.80
5	172.260	137.76	120.00	.0000	54.47	.0000	28.966	661.000	-22064.78	.00
6	294.000	165.83	236.98	.0000	69.32	.0000	28.966	661.000	18558.76	.81
7	291.060	137.16	120.00	.0000	72.40	.0000	28.966	661.000	-18953.43	.00
8	567.000	173.89	272.99	.0000	92.14	.0000	28.966	661.000	24278.73	.79
9	561.330	135.77	120.00	.0000	95.58	.0000	28.966	661.000	-25200.38	.00
10	1015.000	166.48	247.98	.0000	113.44	.0000	28.966	661.000	20300.61	.82
11	1004.850	139.02	140.00	.0000	115.92	.0000	28.966	661.000	-18149.96	.00
12	950.000	139.02	139.30	.0000	113.84	.0000	28.966	661.000	.00	.00
13	921.000	275.78	680.00	.0000	124.25	.0000	28.966	661.000	90400.01	.00
14	841.000	275.78	679.83	.0000	120.96	1.0000	28.966	661.000	.00	.00
15	812.000	364.62	1020.09	.0000	148.54	.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	58.34	1.0000	28.966	664.291	76518.17	.86
17	160.000	535.96	1650.43	.0000	175.45	.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	67.09	.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 B.3 Conventional CAES Thermodynamic Conditions

CONVENTIONAL CAES

TURBINES :		GENERATOR EFFICIENCY = .980				
STA	NO.	BTU/HR	MU	EFFIC. %	LBM/KWHR	PRES. RATIO
16	1	.270+009	.791+002	.860	30.2	5.1
18	2	.531+009	.156+003	.862	15.6	10.6
TOTALS		.801+009	.235+003			
COMPRESSORS :		MOTOR EFFICIENCY = .980				
STA	NO.	BTU/HR	MW	EFFIC. %	LBM/KWHR	PRES. RATIO
2	1	.262+009	.769+002	.814	71.0	6.5
4	2	.801+008	.235+002	.804	101.4	1.8
6	3	.682+008	.200+002	.814	119.1	1.7
8	4	.892+008	.261+002	.788	91.1	1.9
10	5	.746+008	.218+002	.820	108.9	1.8
TOTALS		.574+009	.168+003			
COMBUSTORS :						
STA	NO.	BTU/HR	MW	EFFIC.		
15	1	.214+009	.627+002	1.000		
17	2	.700+009	.205+003	1.000		
TOTALS		.914+009	.266+003			
HEAT EXCHANGERS :						
STA	NO.	BTU/HR	MW	EFFECT.	PPTO	
3	1	-.223+009	-.654+002	.000	.0	
5	2	-.794+008	-.233+002	.000	.0	
7	3	-.682+008	-.200+002	.000	.0	
9	4	-.907+008	-.266+002	.000	.0	
11	5	-.653+008	-.191+002	.000	.0	
13	6	.325+009	.954+002	.000	.0	
19	7	-.325+009	-.954+002	.790	143.9	
TOTALS		-.527+009	-.154+003			

FIGURE B.4. Conventional CAES Component Performance Summary

CONVENTIONAL CAES

POWER IN (KW)	171649.35
POWER OUT (KW)	231175.71
OVER ALL PRESSURE RATIO	68.36
COMPRESSOR SPECIFIC MASS FLOW (LBM/KW-HR IN)	13.86
TURBINE SPECIFIC MASS FLOW (LBM/KW-HR OUT)	10.29
SPECIFIC STORAGE VOLUME (CUBIC FEET/KW-HR OUT)	2.50
PREMIUM FUEL USED (BTU/SEC)	253925.05
CHARGE ENERGY FACTOR (KW-HR OUT/KW-HR IN)	1.35
EQUIVALENT STORAGE EFFICIENCY (%)	81.42
GENERATION HEAT RATE (BTU/KW-HR OUT)	3954.27
ROUND TRIP HEAT RATE (BTU/KW-HR OUT)	11379.33

FIGURE B.5. Conventional CAES Performance Parameters

USER SAMPLE 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 B.6. 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 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.

FIGURE B.6. Adiabatic CAES Cycle Diagram.

Inputs for this analysis are shown in Figure B.7. Formatted input was used in this case. The calculated station conditions are shown in Figure B.8.

1	ADIABATIC CAES															
2	16		1	■												
3	1	2	30	3	4	5	31	8	10	11	32	13	33	15	34	16
4	1	8						14.2	90.					650.	1	
5	2	7		1		1		226.				.835				
6	30	10	2	2	1	2	2				.001		877.			
7	3	4			2	2	2	15.	469.							
8	4	4			2	3	2	5.	236.							
9	5	7		1		4		1215.				.87				
10	31	10	2	5	7	5	5				.001		830.			
11	8	4			2	5	2	25.	125.							
12	10	4			2	5	2	40.	100.							
13	11	4	5	8	4	10	2	25.				1.0				
14	32	10	7	10	2	11	10				.001		.966			
15	13	2		1		11		241.				.85				
16	33	10	2	13	■	13	13				.001		454.			
17	15	4	2	3	4	1	3	2	16.			1.0				
18	34	10	7	3	2	15	3				.001		.966			
19	16	2		1		15		14.7				.90				
20	4															

FIGURE B.7. Inputs for Adiabatic CAES Cycle Analysis

USER SAMPLE 3 - HYBRID CAES

This is an analysis of the A-5 hybrid CAES cycle as described by Glendenning et al. (1979). The cycle diagram is presented in Figure B.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 B.9. Hybrid CAES Cycle Diagram

Inputs for this analysis are shown in Figure B.10. The calculated station conditions are shown in Figure B.11.

USER SAMPLE 4 - PFBC 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 B.12. 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.

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	E
1	14.200	131.38	90.00	.0000	.05	.0000	28.966	650.000	.00	.00
2	226.000	326.73	876.89	.0000	91.58	.0000	28.966	650.000	126981.25	.81
3	211.000	223.18	469.00	.0000	62.04	.0000	28.966	650.000	-67311.06	.00
4	206.000	165.93	236.00	.0000	57.28	.0000	28.966	650.000	-37213.00	.00
5	1215.000	314.62	829.54	.0000	145.79	.0000	28.966	650.000	96452.59	.73
8	1190.000	134.50	125.00	.0000	123.03	.0000	28.966	650.000	-117080.74	.00
10	1150.000	128.10	100.00	.0000	123.15	.0000	28.966	650.000	-4157.52	.00
11	1125.000	308.23	805.03	.0000	140.94	.0000	28.966	650.000	117080.74	.97
13	241.000	219.39	454.01	.0000	65.80	.0000	28.966	650.000	57745.08	.81
15	225.000	322.94	862.29	.0000	90.14	.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 B.8. Adiabatic CAES Thermodynamic Conditions

1	HYBRID CAES														
2	21		1	1											
3	1	2	30	3	4	5	6	7	8	9	10	11	13	32	14 33
4	15	16	35	17	34									661.	1
5	1	8						14.5	59.						
6	2	7		1		1		232.				.87			
7	30	10	2	2	7	2	2			.001		820.			
8	3	4			2	2	2	6.	354.						
9	4	4			2	3	3	.01	98.6						
10	5	7		1		4		493.				.87			
11	6	4			2	5	3	.01	98.6			.87			
12	7	7		1		6		1026.							
13	8	4			2	7	3	.01	98.6						
14	9	4			2	8	3	.00	86.						
15	10	4			2	9	3	.02	608.						
16	11	3	3			10		-624.							
17	13	2		1		11		165.				.85			
18	32	10	2	13	1	13	13			.001		318.			
19	14	4	2	3	4	13	2	5.8				1.			
20	33	10	2	3	2	14	3			.001		784.			
21	15	12		3	1	14		.001652.				1.			
22	16	2		1		15		15.1				.85			
23	35	10	2	16	7	16	16			.001		824.			
24	17	4	9	10	4	16	1	14.7				1.			
25	34	10	7	10	2	17	10			1.		.60			
26	4														

FIGURE B.10 Inputs for Hybrid CAES Cycle Analysis

B.11

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
1	14.500	123.92	59.00	.0000	.10	.0000	28.966	661.000	.00
2	232.000	312.00	819.98	.0000	87.45	.0000	28.966	661.000	124321.47
3	226.000	195.43	356.67	.0000	61.00	.0000	28.966	661.000	-77051.41
4	223.740	132.26	98.60	.0000	64.45	.0000	28.966	661.000	-41759.48
5	493.000	170.99	260.45	.0000	87.21	.0000	28.966	661.000	25602.90
6	488.070	130.76	98.60	.0000	91.76	.0000	28.966	661.000	-26588.73
7	1026.000	166.54	248.32	.0000	113.84	.0000	28.966	661.000	23645.82
8	1015.740	128.27	98.60	.0000	118.54	.0000	28.966	661.000	-25294.46
9	1015.740	124.98	86.00	.0000	119.36	.0000	28.966	661.000	-2173.45
10	995.425	257.39	608.00	.0000	122.69	.0000	28.966	661.000	87524.66
11	624.000	257.39	607.35	.0000	105.74	.0000	28.966	661.000	.00
13	156.727	186.15	318.18	.0000	48.48	.0000	28.966	661.000	47095.07
14	150.927	302.71	783.99	.0000	71.46	.0000	28.966	661.000	77051.41
15	150.927	536.31	1652.00	.0000	174.24	.0000	28.966	661.000	154410.14
16	15.100	312.95	823.82	.0000	67.07	.0000	28.966	661.000	147644.21
17	14.700	180.54	293.47	.0000	7.95	.0000	28.966	661.000	-87524.66

FIGURE B.11 Hybrid CAES Thermodynamic Conditions

FIGURE B. 12. PFBC CAES Cycle Diagram

Inputs for this cycle analysis are shown in Figure 8.13. The calculated station conditions are presented in Figure 8.14.

USER SAMPLE 5 - 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). This analysis illustrates the multi-working fluid capability of the CAESCAP computer code. The compression and generation modes were analyzed separately for this cycle. Cycle diagrams for the compression and generation modes are given in Figures 8.15 and B.16, 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 condensor was neglected and the entering flow rate was used.

```

1  PFBC CAES
2  35,,1,1/
3  1,2,3,30,4,5,31,6,7,32,8,9,33,10,11,12,13,14,15,16,34,24,25,17,18,22,35,19,20,
4  36,40,26,23,21,50/
5  1,8,,,,,14,7,58,7,,,,,761,8,1/
6  2,3,3,,,1,,-14,6/
7  3,7,,1,,2,,60,2/
8  30,10,2,3,7,3,3,,,,,001,,345./
9  4,4,,,2,3,1,59,,160,9/
10 5,7,,1,,4,,243,8/
11 31,10,2,5,7,5,5,,,,,001,,500./
12 6,4,,,2,5,1,240,9,200./
13 7,7,,1,,6,,469,8/
14 32,10,2,7,7,7,7,,,,,001,,377,6/
15 8,4,,,2,7,1,464,8,200./
16 9,7,,1,,8,,999,8/
17 33,10,2,9,7,9,9,,,,,001,,409,3/
18 10,4,,,2,9,1,989,8,120./
19 11,3,3,,,10,,-978,1/
20 12,8,,,,,948,1,120,,,,,731,3,1/
21 13,3,3,,,12,,-938,1/
22 14,4,,,2,13,1,918,1,507,5/
23 15,3,3,,,14,,-888,1/
24 16,2,,1,,15,,225,4/
25 34,10,2,16,7,16,16,,,,,001,,250./
26 24,3,1,25,,16,,,,,-21,8/
27 25,1/
28 17,3,3,,,24,,-220,4/
29 18,12,50,1,2,17,22,201,3,1562,,,,,1./
30 22,1,,,,,150./
31 35,10,5,50,4,22,18,,,,,001,,20,9/
32 19,3,3,,,18,,-199,3/
33 20,2,,1,,19,,15,2/
34 36,10,2,20,7,20,20,,,,,001,,684./
35 40,11,5,20,5,25,2,,,,,752/
36 26,3,1,23,,20,,,,,-33,3/
37 23,1/
38 21,4,13,14,4,26,1,14,9,,,,,25./
39 50,1,,,,,11900./
40 4

```

FIGURE 6.13. Inputs for PFBC CAES Cycle Analysis

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	123.84	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	21.96	.0000	28.966	761.800	52705.54	.90
4	59.000	148.25	160.90	.0000	20.40	.0000	28.966	761.800	-34116.28	.00
5	243.800	230.89	500.39	.0000	68.03	.0000	28.966	761.800	62457.15	.90
6	240.900	157.00	200.00	.0000	63.11	.0000	28.966	761.800	-56292.35	.00
7	469.800	200.03	377.54	.0000	86.48	.0000	28.966	761.800	32785.98	.77
8	464.800	156.19	200.00	.0000	86.02	.0000	28.966	761.800	-33401.82	.00
9	999.800	207.11	409.29	.0000	114.40	.0000	28.966	761.800	38796.87	.75
10	989.800	133.92	120.00	.0000	116.33	.0000	28.966	761.800	-55758.67	.00
11	978.100	133.92	119.92	.0000	115.87	.0000	28.966	761.800	.00	.00
12	948.100	134.08	120.00	.0000	114.72	.0000	28.966	731.300	.00	.00
13	938.100	134.08	119.93	.0000	114.31	.0000	28.966	731.300	.00	.00
14	918.100	232.02	507.50	.0000	114.75	.0000	28.966	731.300	71418.36	.00
15	888.100	232.02	507.69	.0000	113.47	.0000	28.966	731.300	.00	.00
16	225.400	169.26	250.00	.0000	60.17	.0000	28.966	731.300	45895.44	.83
24	225.400	169.26	250.00	.0000	60.17	.0000	28.966	709.500	.00	.00
25	225.400	169.26	250.00	.0000	60.17	.0000	28.966	21.800	.00	.00
17	220.400	169.26	249.93	.0000	59.41	1.0000	28.966	709.500	.00	.00
18	201.300	510.75	1560.10	.0000	168.34	.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	168.08	.0000	28.966	730.411	.00	.00
20	15.200	277.02	683.59	.0000	47.19	.0000	28.966	746.805	170722.52	.89
26	15.200	277.02	683.59	.0000	47.19	.0000	28.966	713.505	.00	.00
23	15.200	277.02	683.59	.0000	47.19	.0000	28.966	33.300	.00	.00
21	14.900	176.64	277.44	.0000	6.70	.0000	28.966	713.505	-71418.36	.72
50	.000	.00	.00	.0000	.0011947.2832		28.966	.000	.00	.00

FIGURE B.14 PFBC CAES Thermodynamic Conditions

FIGURE B.15. Direct Coupled Steam CAES - Compression Mode

FIGURE 8.16. Direct Coupled Steam CAES - Generation Mode

Inputs for the compression and generation mode analyses are given in Figures B.17 and B.18, respectively. The calculated station conditions are given in Figure B.19 for the compression mode and Figure B.20 for the generation mode. By comparing conditions at Stations 12 and 33 in Figure B.19 and Stations 7 and 32 in Figure B.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 (component number 3), which assumes that the outlet flow pressure is equal to the lowest inlet flow pressure.

```

1      CAES / DIRECT COUPLED STEAM - COMPRESSION MODE
2      31.,1/
3      1,2,40,3,4,5,41,6,7,8,42,9,10,12,13,23,43,14,24,15,25,44,16,26,
4      17,11,29,30,31,32,33/
5      1,8,.,.,.,14,7,59,.,.,.,641.8,1/
6      2,7,.,1,.,1,1,61,./
7      40,10,2,2,7,2,2,.,.,.,001,.,348.3/
8      3,4,.,2,2,1,60,4,2/3,6/
9      4,4,.,2,3,1,59,8,200,./
10     5,7,.,1,.,4,1,250,./
11     41,10,2,5,7,5,5,.,.,.,001,.,562.3/
12     6,4,.,2,5,1,247,5,489,1/
13     7,4,.,2,6,1,245,.,200,./
14     8,7,.,1,.,7,1,1020,./
15     42,10,2,8,7,8,8,.,.,.,001,.,620.3/
16     9,4,.,2,8,1,1009,9,547,9/
17     10,4,.,2,9,1,1000,.,125,./
18     12,8,.,.,.,2683,.,470,.,0,0,.,312.4,4/
19     13,4,.,2,12,1,2415,.,1000,./
20     23,2,.,1,.,13,.,530,5/
21     43,10,2,23,7,23,23,.,.,.,001,.,619.8/
22     14,3,1,24,.,23,.,.,.,.,-38.4/
23     24,1/
24     15,4,.,2,14,1,477,4,1000,./
25     25,2,.,1,.,15,.,114,3/
26     44,10,2,25,7,25,25,.,.,.,001,.,645,./
27     16,3,1,26,.,25,.,.,.,.,-22.9/
28     26,1/
29     17,2,.,1,.,16,.,1,7,.,.,.,88/
30     11,4,.,2,17,2,0,0,.,47,1/
31     29,6,.,.,11,1,2683,.,.,.,75/
32     30,4,8,9,4,29,3,.,00,.,.,1.0/
33     31,4,5,6,4,30,3,.,00,.,.,1.0/
34     32,4,2,3,4,31,3,.,00,.,.,1.0/
35     33,3,2,24,26,32/
36     4

```

FIGURE 8.17. Inputs for Direct Coupled Steam CAES Cycle Analysis - Compression Mode

```

1  CAES / DIRECT COUPLED STEAM - GENERATION MODE
2  24,,1/
3  1,2,3,40,4,5,41,7,8,23,43,9,24,10,25,44,11,26,27,12,28,
4  6,31,32/
5  1,8,,,,,970.,125.,,,,1388.9,1/
6  2,4,,,2,1,2,0.0,1000./
7  3,2,,1,,2,,190./
8  40,10,2,3,7,3,3,,,,.001,,534.1/
9  4,4,,,2,3,1,186.,1000./
10 5,2,,1,,4,,14.9/
11 41,10,2,5,7,5,5,,,,.001,,347.3/
12 7,8,,,,,2683.,470.,,0.0,,,312.4,4/
13 8,4,,,2,7,1,2415.,1000./
14 23,2,,1,,8,,530.5/
15 43,10,2,23,7,23,23,,,,.001,,619.8/
16 9,3,1,24,,23,,,,,-38.4/
17 24,1/
18 10,4,,,2,9,1,477.4,1000./
19 25,2,,1,,10,,114.3/
20 44,10,2,25,7,25,25,,,,.001,,645./
21 11,3,1,26,,25,,,,,-22.9/
22 26,1/
23 27,2,,1,,11,,1.7,,,,.88/
24 12,3,1,28,,27,,,,,-45.4/
25 28,1/
26 6,4,,,2,12,2,0.0,,47.1/
27 31,6,,,,6,1,2683.,,,,75/
28 32,3,2,24,26,31,28/
29 4

```

FIGURE 6.18. Inputs for Direct Coupled Steam CAES Cycle Analysis - 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	22.36	.0000	28.966	641.800	44865.95	.89
3	60.400	175.57	273.60	.0000	20.60	.0000	28.966	641.800	-11713.54	.00
4	59.800	157.71	200.00	.0000	20.19	.0000	28.966	641.800	-11463.48	.00
5	250.000	246.43	562.72	.0000	71.86	.0000	28.966	641.800	56941.00	.90
6	247.500	228.11	499.10	.0000	68.08	.0000	28.966	641.800	-11757.16	.00
7	245.000	156.98	200.00	.0000	63.68	.0000	28.966	641.800	-45653.06	.00
8	1020.000	260.34	619.72	.0000	124.23	.0000	28.966	641.800	66335.37	.77
9	1009.900	242.15	547.90	.0000	120.07	.0000	28.966	641.800	-11674.10	.00
10	1000.000	135.17	125.00	.0000	116.45	.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	53153.76	.00
25	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	274.000	42530.72	.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	184.19	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 B.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 BTU/SEC
1	970.000	135.29	125.00	.0000	115.32	.0000	28.966	1378.900	.00
2	970.000	359.33	1000.00	.0000	152.94	.0000	28.966	1378.900	311171.57
3	190.000	239.31	533.96	.0000	61.53	.0000	28.966	1388.900	166493.11
4	186.000	358.86	1000.00	.0000	97.47	.0000	28.966	1388.900	166036.76
5	14.900	193.57	347.07	.0000	11.69	.0000	28.966	1388.900	229567.79
7	2683.000	453.76	470.00	.6451	.00	.0000	18.016	312.400	.00
8	2415.000	1460.38	1000.00	1.5322	.00	1.0000	18.016	312.400	314469.28
23	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	312.400	47171.96
9	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	274.000	.00
24	530.500	1308.75	619.72	1.5625	.00	1.0000	18.016	38.400	.00
10	477.400	1520.99	1000.00	1.7426	.00	1.0000	18.016	274.000	58153.76
25	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	274.000	46530.72
11	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	251.100	.00
26	114.300	1351.17	645.00	1.7641	.00	1.0000	18.016	22.900	.00
27	1.700	1055.67	120.16	1.8336	.00	.9435	18.016	251.100	74198.20
12	1.700	1055.67	120.16	1.8336	.00	.9435	18.016	205.700	.00
28	1.700	1055.67	120.16	1.8336	.00	.9435	18.016	45.400	.00
6	1.700	47.10	79.05	.0915	.00	.0000	18.016	205.700	207463.56
31	2683.000	57.70	82.42	.0964	.00	.0000	18.016	205.700	2181.59
32	1.700	451.33	120.16	.7913	.00	.3542	18.016	312.400	.00

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

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