

# **Brayton Cycle: The Ideal Cycle for Gas-Turbine Engines In Relation to Power Plants**

By Denise Lane

## **Preface:**

Power generation is an important issue today, especially on the West Coast. Demand is outweighing supply because of lack of incentives for the utilities industry to build additional power plants over the past 10-20 years. Electrical innovations (such as the personal computer) were not accounted for in earlier predictions of power utilization and, now, the country is in dire need of streamlining the current power plants while pushing through as many applications as possible for new power plants. In response to this situation, power generation engineers will be in high demand. These engineers must have a thorough understanding of thermodynamics and, in particular, the Brayton cycle. It is the backbone of power generation. In order to deepen knowledge of how the Brayton cycle is applied at power generation plants, an interview was conducted via e-mail with Brian Lawson, who has obtained the P.E. designation and is the Senior Mechanical Engineer for Sierra Pacific Power Company's Tracy Power Generating Station. This station provides a total electrical power output of 454 MW and supplies the majority of the population in northern Nevada. The italicized questions and answers asked and obtained are integrated throughout the various topics to provide further insight and understanding for the beginning engineer entering the power generation field. Further, bolded words are defined in detail at the end of each paragraph.

## **Brayton Cycle/Gas Turbine History:**

The basic gas turbine cycle is named for the Boston engineer, George Brayton, who first proposed the Brayton cycle around 1870.<sup>1</sup> Now, the Brayton cycle is used for gas turbines only where both the compression and expansion processes take place in rotating machinery.<sup>2</sup> John Barber patented the basic gas turbine in 1791.<sup>3</sup> The two major application areas of gas-turbine engines are aircraft propulsion and electric power generation. Gas turbines are used as stationary power plants to generate electricity as stand-alone units or in conjunction with steam power plants on the high-temperature side. In these plants, the exhaust gases serve as a heat source for the steam. Steam power plants are considered external-combustion engines, in which the combustion takes place outside the engine. The thermal energy released during this process is

then transferred to the steam as heat.(2) The gas turbine first successfully ran in 1939 at the Swiss National Exhibition at Zurich. (3) The early gas turbines built in the 1940s and even 1950s had simple-cycle efficiencies of about 17 percent. This was because of low compressor and turbine efficiencies and low turbine inlet temperature due to metallurgical limitations at the time. The first gas turbine for an electric utility was installed in 1949 in Oklahoma as part of a combined-cycle power plant. It was built by General Electric and produced 3.5 MW of power. (2)

In the past, large coal and nuclear power plants dominated the base-load electric power generation. However, natural gas-fired turbines now dominate the field because of their black start capabilities, higher efficiencies, lower capital costs, shorter installation times, better emission characteristics, and abundance of natural gas supplies. The construction cost for gas-turbine power plants are roughly half that of comparable conventional fossil-fuel steam power plants, which were the primary base-load power plants until the early 1980s. More than half of all power plants to be installed in the foreseeable future are forecast to be gas-turbine or combined gas-steam turbine types.

In the early 1990s, General Electric offered a gas turbine that featured a pressure ratio of 13.5 and generated 135.7 MW of net power at a thermal efficiency of 33 percent in simple-cycle operation. A more recent gas turbine manufactured by General Electric uses a turbine inlet temperature of 1425°C (2600°F) and produces up to 282 MW while achieving a thermal efficiency of 39.5 percent in the simple-cycle mode. (2) Current low prices for crude oil make fuels such as diesel, kerosene, jet-engine fuel, and clean gaseous fuels (such as natural gas) the most desirable for gas turbines. However, these fuels will become much more expensive and will eventually run out. Provisions must therefore be made to burn alternative fuels.<sup>4</sup>

*Q: Do I understand correctly that you use the gas turbine exhaust heat to serve as a heat source for steam turbines to produce even more power?*

*A: The Pinon Pine unit is a “combined cycle” which has a heat recovery boiler attached to the exhaust of the combustion turbine to produce about 22 MW of power from a steam turbine (Rankine cycle) that is located next door.*

*Q: I understand that you are in the process of trying to use diesel instead of gas? Is the diesel providing enough expansion to turn the turbines as fast as needed to produce the same electric power produced from gas and/or proving to be economical in the trade-off?*

*A: There is only a small difference in the performance between firing a combustion turbine on natural gas and diesel. The cost of diesel, however, is typically much higher than natural gas on a \$/MMBtu basis.*

**Brayton Cycle Components:**

Gas turbines usually operate on an open cycle, as shown in Figure 1. Fresh air at ambient conditions is drawn into the **compressor**, where its temperature and pressure are raised. The high-pressure air proceeds into the **combustion** chamber, where the fuel is burned at constant pressure. (2) The resulting high-temperature gases then enter the **turbine**, where they expand to the atmospheric pressure through a row of nozzle vanes.<sup>5</sup> This expansion causes the turbine blade to spin, which then turns a shaft inside a magnetic coil. When the shaft is rotating inside the magnetic coil, electrical current is produced. The exhaust gases leaving the turbine in the open cycle are not re-circulated.

Figure 1 – An Open Cycle Gas-Turbine Engine

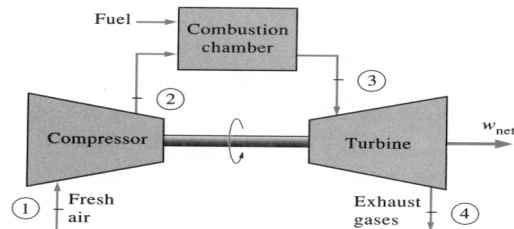
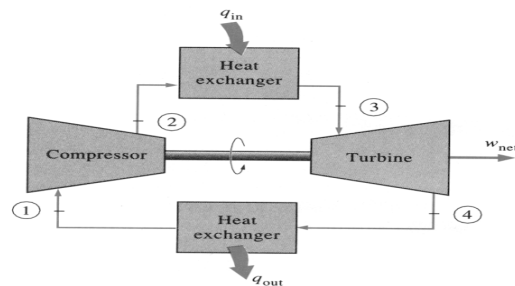


Figure 2 – A Closed Cycle Gas-Turbine Engine



The open gas-turbine cycle can be modeled as a closed cycle as shown in Figure 2 by utilizing the **air-standard assumptions**. Here the compression and expansion process remain the same, but a constant-pressure heat-rejection process to the ambient air replaces the combustion process. The ideal cycle that the working fluid undergoes in this closed loop is the Brayton cycle, which is made up of four **internally reversible processes**:

- 1-2 **Isentropic** compression (in a compressor)
- 2-3 Constant pressure heat addition
- 3-4 Isentropic expansion (in a turbine)
- 4-1 Constant pressure heat rejection (2)

**Compressor:** (See Figure 3) Efficient compression of large volumes of air is essential for a successful gas turbine engine. This has been achieved in two types of compressors, the axial-flow compressor and the centrifugal – or radial-flow compressor. Most power plant compressors are axial-flow compressors. The object of a good compressor design is to obtain the most air through a given diameter compressor with a minimum number of stages while retaining relatively high efficiencies and aerodynamic stability over the operating range. Compressors contain a row of rotating blades followed by a row of stationary (stator) blades. A stage consists of a row of rotor and a row of stator blades. All work done on the working fluid is done by the rotating rows, the stators converting the fluid kinetic energy to pressure and directing the fluid into the next rotor. The fluid enters with an initial velocity relative to the blade and leaves with a final relative velocity at a different angle. (3)

Figure 3 – An Axial-Flow Compressor



**Combustion/Combustor:** (See Figure 4) Combustion is the chemical combination of a substance with certain elements, usually oxygen, accompanied by the production of a high temperature or transfer of heat. The function of the combustion chamber is to accept the air from the compressor and to deliver it to the turbine at the required temperature, ideally with no loss of pressure. (3) Essentially, it is a direct-fired air heater in which fuel is burned with less than one-third of the air after which the combustion products are then mixed with the remaining air.<sup>6</sup> For

the common open-cycle gas turbine, this requires the internal combustion of fuel. This means the problem of fuel operation, mixing and burning, must be addressed. Fuel is commonly gaseous or liquid. Solid fuel has not yet advanced beyond the experimental stage. Gaseous or liquid fuels are usually hydrocarbons. Gases usually being natural gas, mostly methane, and butane. Liquids may range from highly refined gasoline through kerosene and light diesel oil to a heavy residual oil (Bunker C or No. 6 fuel oil). Combustion itself is seldom difficult. The difficulty arises in the combination of combustion with low-pressure loss in a size of combustor compatible with the high power-weight, high specific output potentialities, or the rotating elements. Almost any fuel can be burnt successfully if sufficient pressure drop is available to provide the necessary turbulence for mixing of air and fuel and if sufficient volume is available to give the necessary time for combustion to be completed. (3)

Figure 4 – A Combustion Chamber Can



**Turbine:** (See Figures 5 and 6) Gas turbines move relatively large quantities of air through the cycle at very high velocities. Among the mechanical characteristics of gas turbine engines are very smooth operation and absence of vibration due to reciprocating action. The high rotational speeds utilized require very accurate rotor balancing to avoid damaging vibration. Rotor parts are highly stressed with low factors of safety. Blades are very finely tuned to avoid resonant vibration. Gas turbines have relatively few moving (and no sliding) parts and are not subjected to vibratory forces. As a result, they are highly reliable when properly designed and developed. (1) The gas turbine in its most common form is a heat engine operating through a series of processes. These processes consist of compression of air taken from the atmosphere, increasing of gas temperature by the constant-pressure combustion of fuel in the air, expansion of the hot

gases, and finally, discharging of the gases to atmosphere, in a continuous flow process. It is similar to the gasoline and Diesel engines in its working medium and internal combustion, but is like the steam turbine in the steady flow of the working medium. The compression and expansion processes are both carried out by means of rotating elements in which the energy transfer between fluid and rotor is effected by means of kinetic action, rather than by positive displacement as in reciprocating machinery. (3)

Figure 5 – Inside a Turbine Chamber

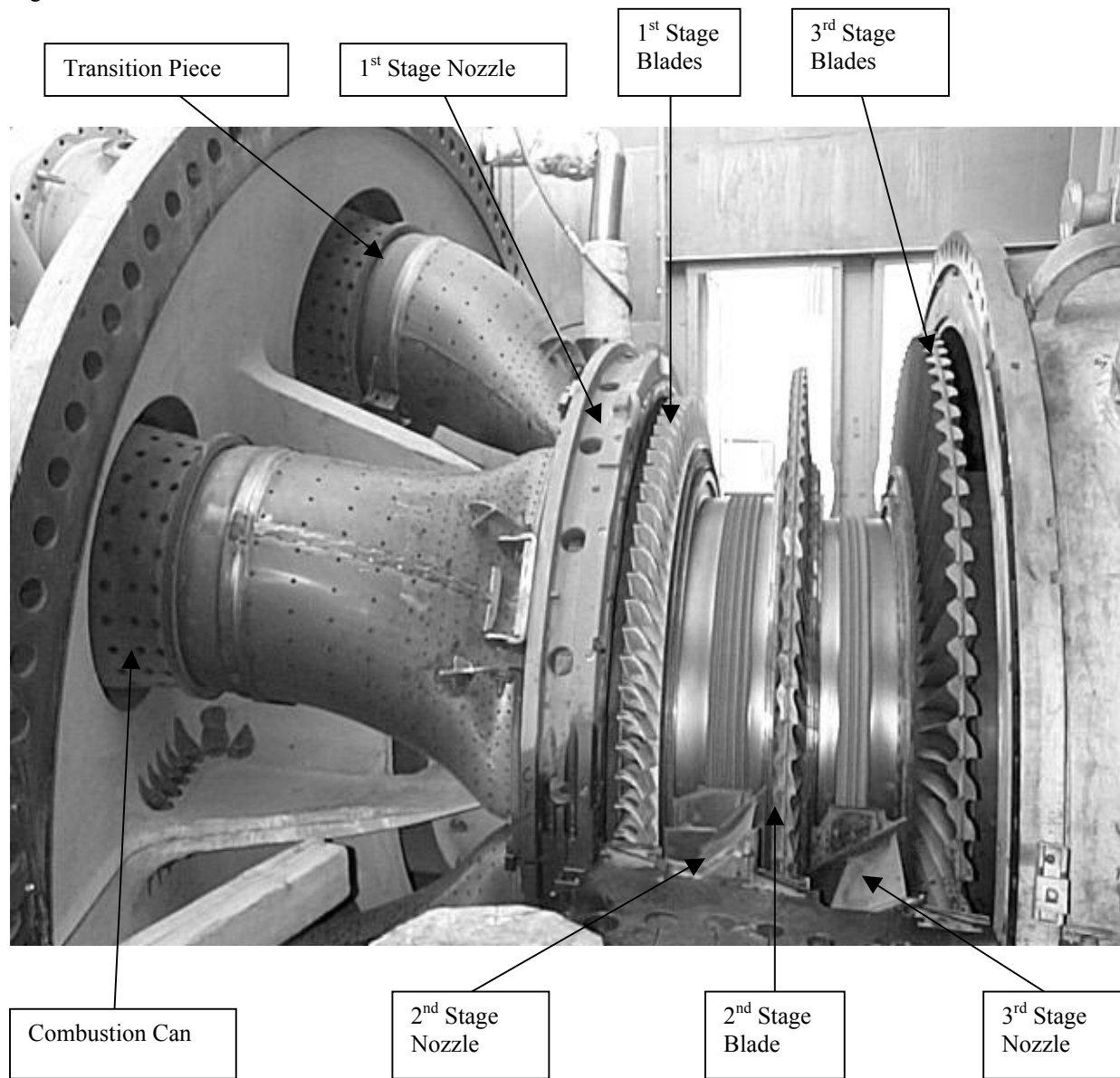


Figure 6 – A Turbine's 1<sup>st</sup> Stage Blades

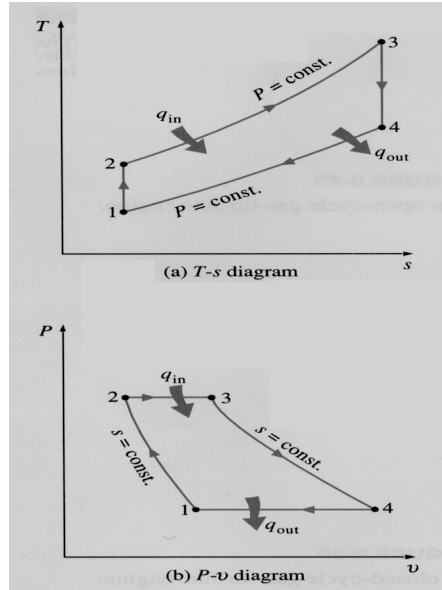


**Air-standard assumptions:** Assumptions that the compression and expansion processes are adiabatic (insulated) and reversible (isentropic), that there is no pressure drop during the heat addition process, and that the pressure leaving the turbine is equal to the pressure entering the compressor. (3)

**Internally reversible processes:** Thermodynamics states that, for given temperature limits, a completely reversible cycle has the highest possible efficiency and specific work output, reversibility being both mechanical and thermal. Mechanical reversibility is a succession of states in mechanical equilibrium, i.e. fluid motion without friction, turbulence, or free expansion. Thermal reversibility is a consequence of the Second Law of thermodynamics, which states that heat must be added only at the maximum temperature of the cycle and rejected at the minimum temperature.

**Isentropic:** Processes held at constant volume or constant pressure.

Figure 7 – T-s and P-v Diagrams of an Ideal Brayton Cycle



The **T-s** and **P-v** diagrams of an ideal Brayton cycle are shown in Figure 7. All four processes of the Brayton cycle are executed in steady flow devices so they should be analyzed as steady-flow processes. When the changes in kinetic and potential energies are neglected, the energy balance for a steady-flow process can be expressed, on a unit-mass basis, as

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

Therefore, heat transfers to and from the working fluid are

$$q_{in} = h_3 - h_2 = C_p(T_3 - T_2)$$

and

$$q_{out} = h_4 - h_1 = C_p(T_4 - T_1)$$

Then the thermal efficiency of the ideal Brayton cycle under the cold air-standard assumptions becomes

$$\eta_{th, Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{T_1 \left( \frac{T_4}{T_1} - 1 \right)}{T_2 \left( \frac{T_3}{T_2} - 1 \right)}$$

Processes 1-2 and 3-4 are isentropic, and  $P_2 = P_3$  and  $P_4 = P_1$ . Thus,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{(k-1)}{k}} = \left(\frac{P_3}{P_4}\right)^{\frac{(k-1)}{k}} = \frac{T_3}{T_4}$$

Substituting these equations into the thermal efficiency relation and simplifying give

$$\eta_{\text{th, Brayton}} = 1 - \frac{1}{\left(r_p\right)^{\frac{(k-1)}{k}}}$$

where

$$r_p = \frac{P_2}{P_1}$$

is the pressure ratio and  $k$  is the **specific heat ratio**. Under the cold-air assumptions, the thermal efficiency of an ideal Brayton cycle depends on the pressure ratio of the gas turbine and the specific heat ratio of the working fluid (if different from air). The thermal efficiency increases with both of these parameters, which is also the case for actual gas turbines. (2)

*Q: In textbooks, kinetic and potential energies are neglected in the energy balances. Do you also ignore kinetic and potential energies?*

*A: The change in kinetic and potential energies are usually considered insignificant for combustion turbines. They are almost always ignored in energy balances and performance calculations.*

*Q: Do you consider the compression and expansion process to be isentropic in calculations?*

*A: No, we do not consider compression and expansion processes to be isentropic. In some cases, we calculate the isentropic efficiency of a turbine or compressor, which as you know is the ratio of actual to ideal enthalpy change in the process. This is done so that we can track the condition of the equipment. If we considered the processes to be isentropic, we would not be able to make meaningful comparisons when testing the equipment.*

*Q: What are the average compressor and turbine fluid exit temperatures?*

*A: Compressor discharge temperatures range from 700-730 °F. Turbine exhaust temperatures are about 1000 – 1200 °F.*

**T-s and P-v diagrams:** Temperature-Entropy and Pressure-Volume Diagrams.

**Specific heat ratio:** A physical property of a material. The specific heat is defined as the amount of heat required to raise a unit of mass of a substance one degree.<sup>7</sup> The specific heat of air is independent of pressure within the limits of gas turbine operation, but varies considerably with temperature. Furthermore, the internal combustion of fuel causes the expansion gas to contain products of combustion, principally CO<sub>2</sub> and H<sub>2</sub>O vapor, both having higher values of specific heat than that of pure air. Previously, the specific heat has been taken to be constant throughout the cycle. This assumption would seem to introduce a considerable error, because the difference between the cold air and hot gas values is approximately 20%. However, although there is an error, it is much less than this value, because of the compensating effect of the varying specific heat ratio. As the specific heat increases with temperature, the isentropic index specific heat decreases along with the change in pressure for a given pressure ratio. The change of enthalpy then becomes neutralized, as it is temperature dependent. Actually, the specific heat of air and of combustion gases changes continually during compression and expansion and for a precise calculation, an integration process is required. (3)

The highest temperature in the cycle occurs at the end of the combustion process (state 3), and the maximum temperature that the turbine blades can withstand limits the system. This also limits the pressure ratios that can be used in the cycle. For fixed minimum and maximum temperatures, the Brayton cycle first increases with the pressure ratio, reaching a maximum, and then decreases. In most common designs, the pressure ratio of gas turbines ranges from about 11 to 16.

Increasing the turbine inlet temperatures and, therefore, the pressure ratios has been the primary approach taken to improve gas-turbine efficiency. The inlet temperatures have increased from about 540°C (1000°F) in the 1940s to 1425°C (2600°F) today. The development of new materials and cooling techniques for critical components such as coating the turbine blades with ceramic layers and cooling the blades with the discharge air from the compressor made temperature increases possible. Maintaining high turbine inlet temperatures with an air-

cooling technique requires the combustion temperature to be higher to compensate for the cooling effect of the cooling air. But higher combustion temperatures increase the amount of nitrogen oxides (NO<sub>x</sub>), which are responsible for the formation of ozone at ground level and smog. Using steam as the coolant allows an increase in the turbine inlet temperatures by 200°F without an increase in the combustion temperature. Steam is also a much more effective heat transfer medium than air. (2)

*Q: What is the maximum temperature that the turbine blades can withstand? Do you operate the combustion process at this temperature?*

*A: The GE 6FA combustion turbine is designed to have a firing temperature of 2350°F. The engine is operated at this temperature nearly 100% of the time. This is very close to the temperature limit for the turbine metallurgy. In fact, we have had blade failures in the turbine that was attributed to the firing temperature (and blade geometry). The blades were redesigned, and the problem has become less severe.*

*Q: In the Pinon Pine station, my understanding is that the fuel is combusted twice to produce cleaner emissions. Is this correct? Do NO<sub>x</sub> emission permissible levels keep you from operating at the maximum temperature of the turbine blade? If so, how much does this reduce the efficiency to meet regulation standards and what is the standard in Nevada?*

*A: We can meet our emission limits and still maintain firing temperature. On the 6FA unit, injecting steam into the turbine near the combustion zone limits the emissions. The steam helps reduce the maximum flame temperature and limits NO<sub>x</sub> production. Fuel is only combusted once on all of our gas turbines. The 7EA's utilize a "pre-mix" system which blends natural gas with air prior to combustion (this is the NO<sub>x</sub> control for these units). The "pre-mix" mode results in a cooler flame, which limits NO<sub>x</sub> production. The combustor is designed so that excess CO can be "burned-out" prior to the combustion gases entering the turbine.*

*Q: Do you use the maximum operating temperature, with the above considerations, to set the pressure ratios in the cycle? If so, what minimum temperature do you use for the compression cycle as the fresh-air temperature varies from day-to-day?*

*A: The firing temperature of the combustion turbine is used as the primary control for the unit. The unit tries to maintain 2350°F firing temperature under all ambient conditions. This sets the mass flow through the machine, which ultimately sets the pressure ratios for the cycle.*

*Q: At what pressure ratios do the various gas turbine engines operate?*

*A: The GE 6FA combustion turbine that is used in the Pinon Pine combined cycle has an 18-stage compressor, which can produce a compression ratio of about 15. We also have (2) GE 7EA's, which have 17 stages of compression, and generate a compression ratio of about 12.2.*

*Q: Do you use excess steam to cool the gas turbine blades to allow higher gas-turbine inlet temperatures?*

*A: Not at Tracy. GE does have a new generation of combustion turbine (9H) that uses steam for cooling the blades.*

The air in gas turbines supplies the necessary oxidant for the combustion of the fuel. It also serves as a coolant to keep the temperature of various components within safe limits by drawing in more air than is needed for the complete combustion of the fuel. In gas turbines, air-fuel mass ratios are usually greater than or equal to 50. Because of this high ratio, treating the combustion gases as air will not cause any appreciable error. Also, the mass flow rate through the turbine will be greater than that through the compressor, the difference being equal to the mass flow rate of the fuel. So assuming a constant mass flow rate throughout the cycle will yield conservative results for open-loop gas-turbine engines. (2)

*Q: What air-fuel mass ratio is obtained in the Pinon Pine cycle? If the ratio is less than 50, how is the specific heat ratio compensated in your calculations?*

*A: The design air to fuel mass ratio is about 40 for the Pinon 6FA unit. Specific heat and other gas properties are calculated based on gas composition using tables and programs published by ASME and others. A good reference book is Sawyer's Gas Turbine Engineering Handbook.*

*Q: The mass flow rate through the turbine will be greater than that through the compressor, the difference being equal to the mass flow rate of the fuel. Do you measure the mass flow rate of the fuel and compensate for it, or do you just assume the same mass flow rate as the rest of the cycle?*

*A: Fuel flow is measured and appropriate adjustments are made in the performance calculations.*

In gas-turbine power plants, the ratio of the compressor work to the turbine work, called the back work ratio, is very high. Usually, more than one-half of the turbine work output is used to drive the compressor. Low compressor and turbine adiabatic efficiencies make the ratio even higher. This is in complete contrast with steam power plants, where the back work ratio is only a few percent. (2)

*Q: What is the back-work ratio of the gas turbines compared to the steam turbine?*

*A: About half of the power generated by a combustion turbine is used to turn the compressor. For a steam turbine, the parasitic load is usually in the 2%-5% range, depending on the type of plant.*

### **Deviation of Actual Gas-Turbine Cycles from Idealized Ones:**

The actual gas turbine cycle differs from the ideal Brayton cycle. Some pressure drop during the heat addition and rejection processes is unavoidable. The actual work input to the

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

compressor will be more, and the actual work output from the turbine will be less because of irreversibilities. The deviation of actual compressor and turbine behavior from the idealized isentropic behavior can be accurately accounted for by utilizing the adiabatic efficiencies of the turbine and compressor defined as

$$\eta_C = \frac{w_s}{w_a} = \frac{h_1 - h_{2s}}{h_1 - h_{2a}}$$

where states 2a and 4a are the actual exit states of the compressor and the turbine, respectively, and 2s and 4s are the corresponding states for the isentropic case. (2)

*Q: What are the efficiencies of the turbine and compressor?*

*A: Isentropic efficiencies range from 85% to 90%.*

*Q: What are the thermal efficiencies and net power production of the turbines at Tracy?*

*A: The thermal efficiency of the 6FA-combustion turbine is approximately 32% (based on the higher heating value of the fuel). The 7EA's have a thermal efficiency of about 28%. This difference can primarily be attributed to the higher firing temperature of the 6FA machine. Net power output is about 68MW for the 6FA and the net power output for a 7EA is about 72MW.*

*There are also three older steam units (Rankine cycle) at Tracy ( $T1 = 53MW$ ,  $T2 = 83MW$ , and  $T3 = 108MW$ ), which have thermal efficiencies ranging from about 28% to about 31%. We also have two old (1961)-combustion turbines, which have thermal efficiencies of about 22%.*

### **Summary:**

Comparison of the actual Brayton cycle presented in the textbook versus the actual power plant figures from the Tracy power plant can be examined to provide an idea of what “real-world” answers entail. In comparing the standard textbook for thermodynamics with the interview conducted with Brian Lawson, the conclusion is that while the Brayton cycle is the backbone of power generations calculations, there is a lot more involved than what is presented in the standard textbooks. The textbooks tend to idealize the calculations and only vaguely account for physical actualities. While the interview was not exhaustive, it should provide a basic understanding of actualities not given in textbooks. As power generation is a major component in today's society, the need for a deeper understanding of power generation becomes imperative in fields of both generation and utilization.

### **Homework Problem:**

A simple ideal Brayton cycle with air as the working fluid has a pressure ratio of 10. The air enters the compressor at 520R and the turbine at 2000R. Accounting for the variation of the specific heats with temperature determine (a) the air temperature at the compressor and turbine exits, (b) the net work output, and (c) the thermal efficiency.

## Endnotes

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- <sup>1</sup> **Sawyer's Gas Turbine Engineering Handbook Volume 1**, "Thermodynamics and fundamentals of the Gas Turbine Cycle", Howard, C.P., Gas Turbine Publications, Inc.
- <sup>2</sup> **Thermodynamic An Engineering Approach**, Cengel, Y.A., Boles, M.A., McGraw-Hill Book Co.
- <sup>3</sup> **Introduction to the Gas Turbine**, Shepherd, D.G., D. Van Nostrand Co., Inc.
- <sup>4</sup> **Mechanical Engineering**, "The Keys to Cogeneration and Combined Cycles", Feb. 1988: 64
- <sup>5</sup> **Sawyer's Gas Turbine Engineering Handbook Volume 1**, "Design of the Gas Turbine Engine", Dundas, R.E., Gas Turbine Publications, Inc.
- <sup>6</sup> **Sawyer's Gas Turbine Engineering Handbook Volume 1**, "Combustor Design", Hazard, H.R., Gas Turbine Publications, Inc.
- <sup>7</sup> **Fundamentals of Gas Turbines**, Bathie, W.W., John Wiley & Sons