Thermodynamics Fundamentals for Energy Conversion Systems

Renewable Energy Applications

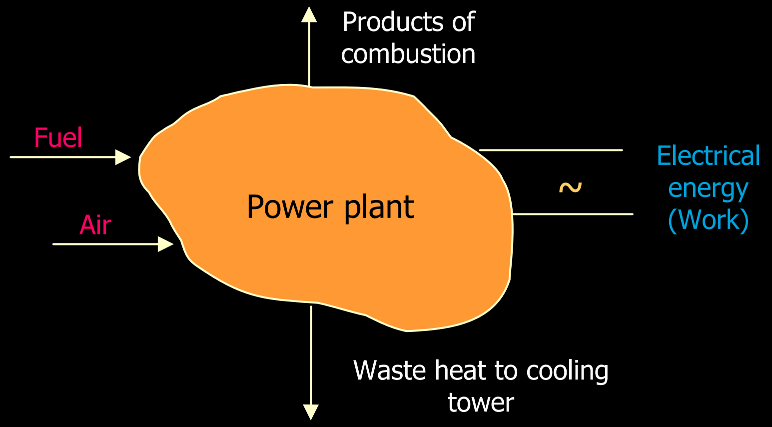
The study of the laws that govern the conversion of energy from one form to the other

Energy Conversion

Concerned with the transformation of energy from sources such as fossil fuel and radiation from Sun into conveniently used forms such as electrical energy, propulsive energy, heating and cooling.

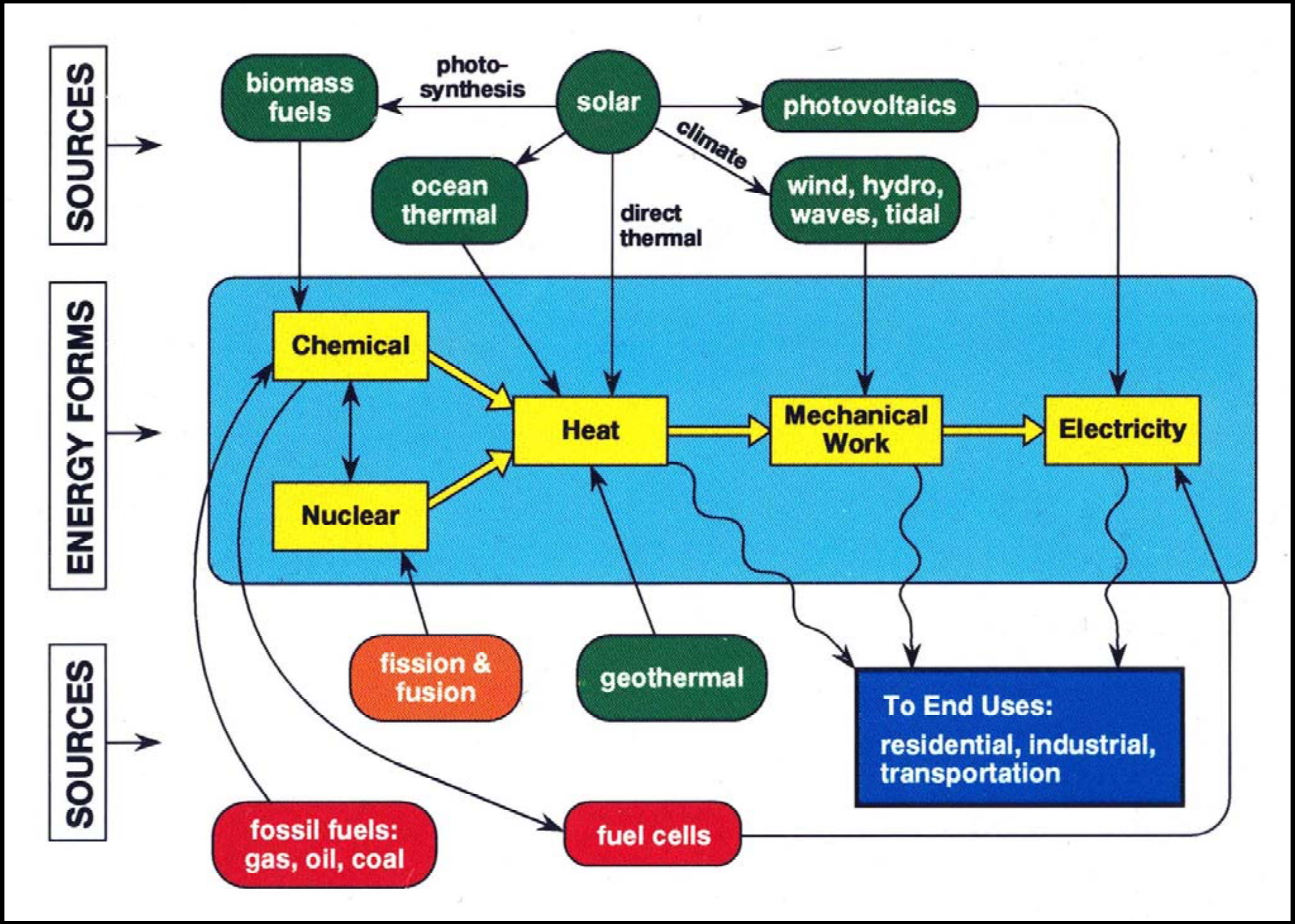
Forms of energy: Kinetic, potential, thermal, chemical, electromagnetic etc.

Thermodynamics is the study which seeks to establish quantitative relationships among macroscopic variables (like pressure, temperature, molecular concentrations etc.) which describe an arbitrary physical system (system being very large compared with atomic dimensions) in an equilibrium state.

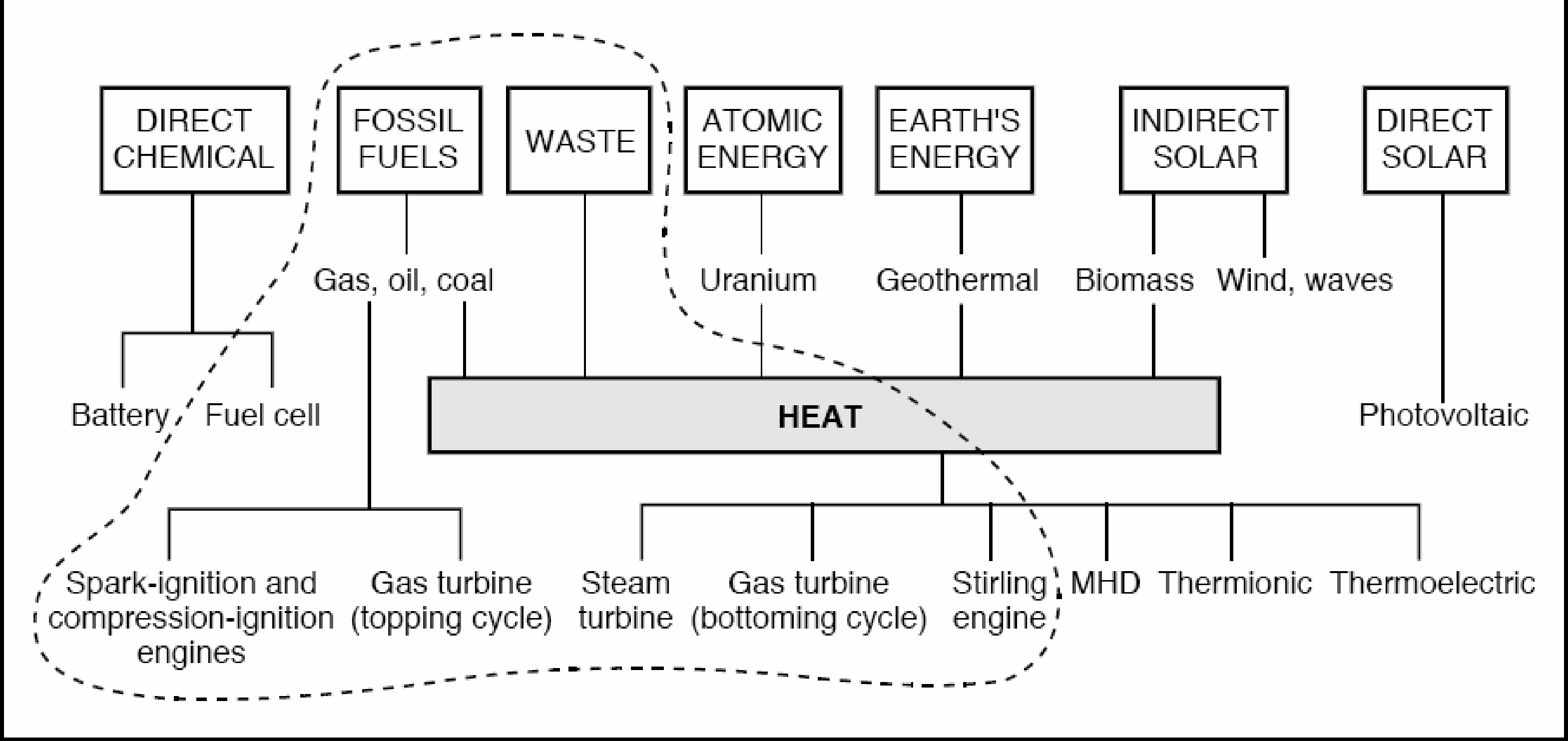


Objective: Convert the availability of the fuel into work in the most efficient manner, taking into consideration cost, size, safety and environmental concerns.

Energy Sources and Conversion Processes



Energy Conversion Technologies



Laws of Thermodynamics

The Zeroth Law of Thermodynamics: *If two systems are in thermal equilibrium with a third, then they are in thermal equilibrium with each other.* This law is the basis of temperature measurement.

First Law of Thermodynamics: *The change in internal energy of a closed system is equals to the heat added to the system (or absorbed from the environment) minus the work done by the system (or on the environment).* This law is a consequence of conservation of energy.

While attempting to transform heat into work with full efficacy, we quickly learned that always some heat would escape into the surrounding environment as wasted energy (recall that energy can not be destroyed). This wasted energy can never be fully converted into anything useful.

Second Law of Thermodynamics: *It is impossible to construct an engine which, operating in a cycle, will produce no other effect than the extraction of heat from a single heat reservoir and the performance of an equal amount of work.*

It imposes a limitation on energy transformations other than that imposed by the first law.

Entropy

The second law states that heat flows naturally from regions of higher temperature to regions of lower temperature, but that it will not flow naturally the other way.

Heat can be made to flow from a colder region to a hotter region, which is exactly what happens in an air conditioner, but heat only does this when it is forced. On the other hand, heat flows from hot to cold spontaneously.

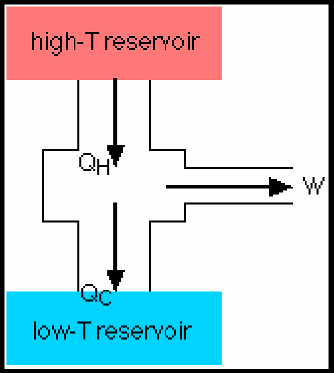
Entropy is an indicator of the temperature of energy. A given amount of thermal energy has low entropy when it is at high temperature, and the same amount of energy has higher entropy when it is at lower temperature.

Heat is energy, and with energy, size matters. With temperature, it does not.

The radiant energy that arrives at Earth from the Sun at a temperature of 6000 K is a very low-entropy form of heat.

Thermal Efficiency

A power cycle receives heat at a high temperature, converts some of this energy into mechanical work, and rejects reminder at a lower temperature. By virtue of second law of thermodynamics, no power cycle can convert more heat into work than the Carnot cycle.



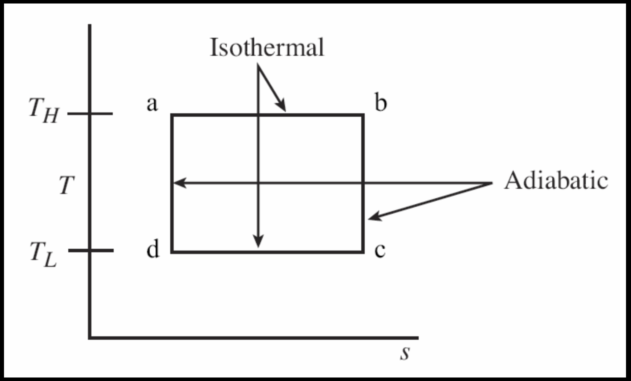
The theoretical maximum efficiency of any heat engine is defined by the Carnot Cycle. The Carnot cycle is a hypothetical engine involving four processes: an adiabatic reversible compression and expansion and a constant temperature heat addition and rejection.

The Carnot heat engine (the ideal heat engine) has an efficiency equal to $(T_H - T_C)/T_H$ where T_H is the temperature of the hot source and T_C is the temperature of the cold sink.

$$\eta_{thermal} = 1 - \frac{T_c}{T_H}$$

The Carnot Cycle

1. **Reversible isothermal expansion of the gas at the "hot" temperature, T_H.**
   During this step, the expanding gas causes the piston to do work on the surroundings. The gas expansion is driven by absorption of heat from the high temperature reservoir.
2. **Reversible adiabatic expansion of the gas.**
   For this step we assume the piston and cylinder are thermally insulated, so that no heat is gained or lost. The gas continues to expand, doing work on the surroundings. The gas expansion causes it to cool to the "cold" temperature, T_C.
3. **Reversible isothermal compression of the gas at the "cold" temperature, T_C.** Now the surroundings do work on the gas, causing heat to flow out of the gas to the low temperature reservoir.
4. **Reversible adiabatic compression of the gas.**
   Once again we assume the piston and cylinder are thermally insulated. During this step, the surroundings do work on the gas, compressing it and causing the temperature to rise to T_H. At this point the gas is in the same state as at the start of step 1.



The Carnot Cycle

The amount of work produced by the Carnot cycle, w_c, is the difference between the heat absorbed in step 1, q_H and the heat rejected in step 3, q_C. Or in equation form:

$$w_c = q_H - q_C \qquad (1)$$

The efficiency of a heat engine is defined as the ratio of the work done on the surroundings to the heat input at the higher temperature. Thus for the Carnot cycle:

$$\eta = \frac{w_c}{q_H} = \frac{q_H - q_C}{q_H} = 1 - \frac{q_C}{q_H} \qquad (2)$$

It can also be shown that for the Carnot cycle $q_C/q_H = T_C/T_H$, so in terms of temperature, the efficiency is:

$$\eta = 1 - \frac{T_C}{T_H} \qquad (3)$$

From Equation 3 it is clear that in order to maximize efficiency one should maximize T_H and minimize T_C.

The Carnot Cycle

Carnot's theorem states that *No engine operating between two heat reservoirs can be more efficient than a Carnot engine operating between the same reservoirs.* Thus, Equation 3 gives the maximum efficiency possible for any engine using the corresponding temperatures. A corollary to Carnot's theorem states that: *All reversible engines operating between the same heat reservoirs are equally efficient.* So Equation 3 gives the efficiency of any reversible engine.

In reality it is not practical to build a thermodynamically reversible engine, so real heat engines are less efficient than indicated by Equation 3. Nevertheless, Equation 3 is extremely useful for determining the maximum efficiency that could ever be expected for a given set of thermal reservoirs.

A more useful question to ask is : what is the efficiency when the engine is working at maximum power? A simple analysis will give

$$\eta_{\max imum-power} = 1 - \sqrt{\frac{T_c}{T_H}}$$

Stirling Engine

Stirling-cycle engines are among the most efficient practical heat-engines ever built.

The gasses used inside a Stirling engine never leave the engine. There are no exhaust valves that vent high-pressure gasses, as in a gasoline or diesel engine, and there are no explosions taking place. Because of this, Stirling engines are very quiet.

The Stirling cycle uses an external heat source, which could be anything from gasoline to solar energy to the heat produced by decaying plants. No combustion takes place inside the cylinders of the engine.

The key principle of a Stirling engine is that a fixed amount of a gas is sealed inside the engine. The Stirling cycle involves a series of events that change the pressure of the gas inside the engine, causing it to do work.

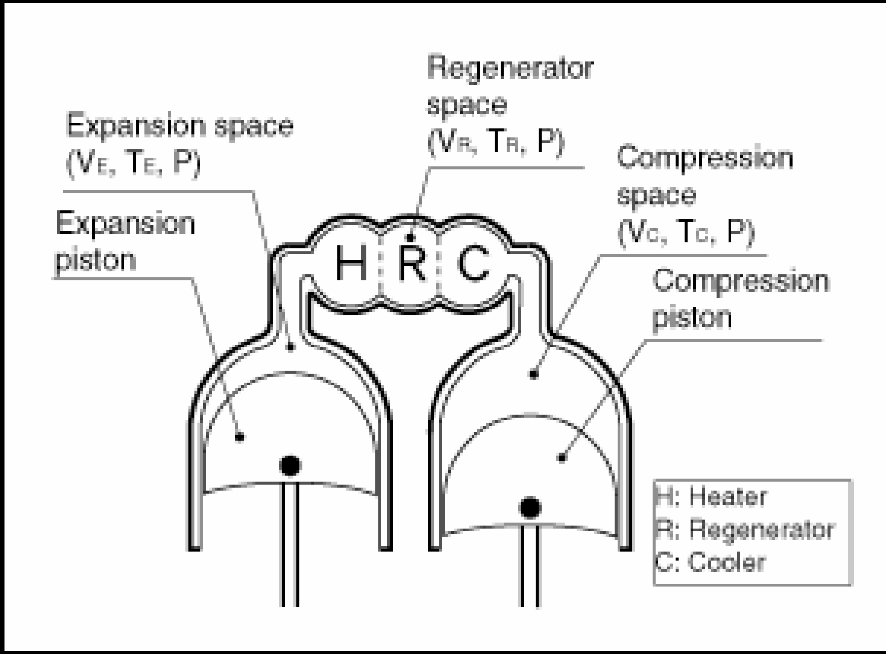
There are several properties of gasses that are critical to the operation of Stirling engines:

If you have a fixed amount of gas in a fixed volume of space and you raise the temperature of that gas, the pressure will increase.

If you have a fixed amount of gas and you compress it (decrease the volume of its space), the temperature of that gas will increase.

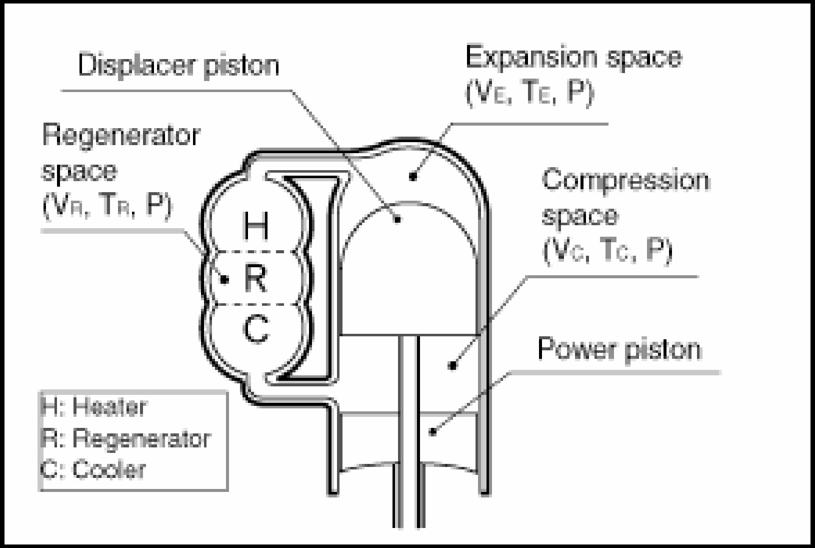
Stirling Engine

The simplified engine uses two cylinders. One cylinder is heated by an external heat source, and the other is cooled by an external cooling source. The gas chambers of the two cylinders are connected, and the pistons are connected to each other mechanically by a linkage that determines how they will move in relation to one another.

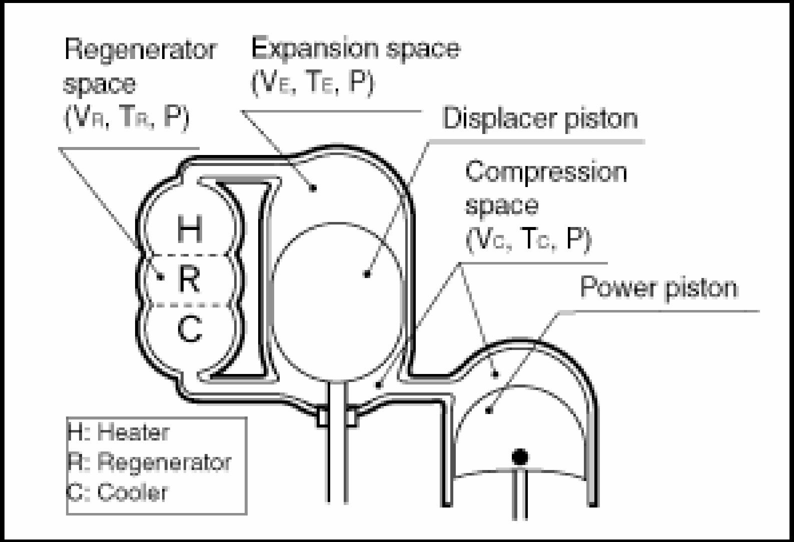


ALPHA-TYPE STIRLING ENGINE

Stirling Engine



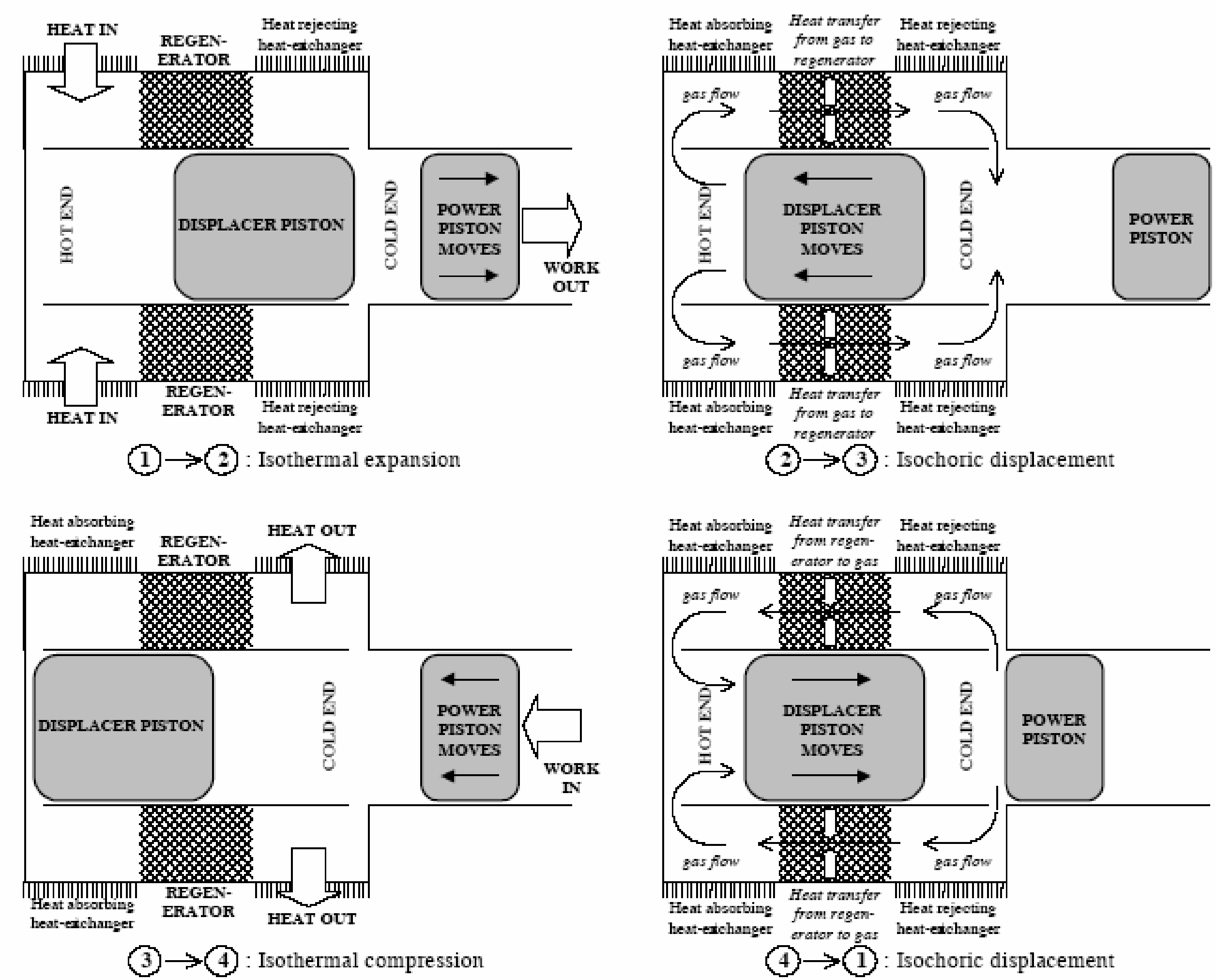
Beta type Stirling Engine

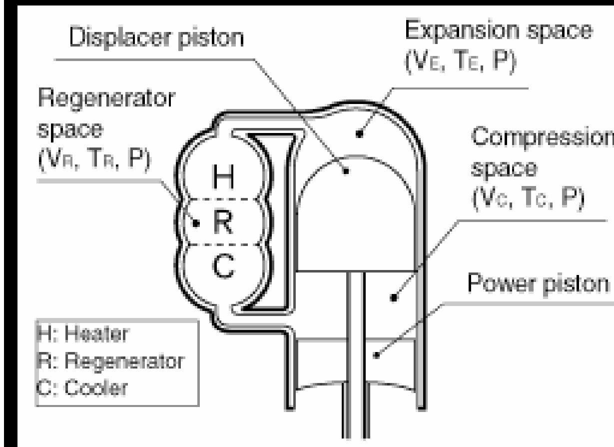


Gamma type Stirling Engine

Ref: G. Walker., Stirling Engines, (1980), Oxford Univ. Press.

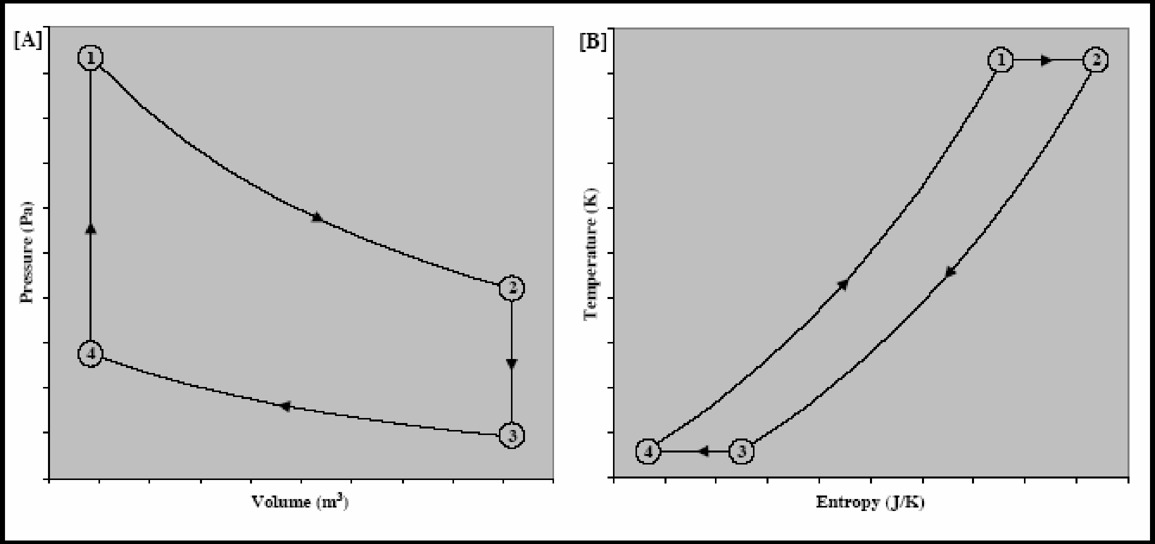
Thermodynamic Processes in β configuration





Regenerator: Acts as a thermal barrier between the hot and cold ends of the machine and also store some of the thermal energy. Usually consists of a mesh material and heat is transferred as the working gas is blown through the regeneration mesh. Heat is either deposited or withdrawn from the regenerator depending on the direction the gas is moving.

Thermodynamic Processes in an Ideal Stirling Cycle



1 ⟶ 2: Isothermal (Constant Temperature) expansion

2 ⟶ 3: Constant volume displacement

3 ⟶ 4: Isothermal compression

4 ⟶ 5: Constant volume displacement

Efficiency of an Ideal Stirling Cycle

The equation for work (represents energy out of the system) :

$$W = -mR\ln\left(\frac{V_2}{V_1}\right)(T_H - T_L)$$

For isothermal expansion process, the heat input is given by:

$$Q_H = mRT_H\ln\left(\frac{V_2}{V_1}\right)$$

The efficiency is defined by:

$$\eta = \frac{-W}{Q_H} = \frac{(T_H - T_L)}{T_H} = \eta_{carnot}$$

Stirling Engine Analysis

1. INTRODUCTION

The *Schmidt theory* is one of the isothermal calculation methods for Stirling engines. It is the most simple method and very useful during Stirling engine development.
This theory is based on the isothermal expansion and compression of an ideal gas.

2. ASSUMPTION OF SCHMIDT THEORY

The performance of the engine can be calculated using a P-V diagram. The volume in the engine is easily calculated by using the internal geometry. When the volume, mass of the working gas and the temperature is decided, the pressure is calculated using an ideal gas method as shown in equation (1).

$$pv = mRT \qquad (1)$$

The engine pressure can be calculated under following assumptions:
(a) There is no pressure loss in the heat-exchangers and there are no internal pressure differences.
(b) The expansion process and the compression process changes isothermal.
(c) Conditions of the working gas is changed as an ideal gas.
(d) There is a perfect regeneration.
(e) The expansion dead space maintains the expansion gas temperature - T_E, the compression dead space maintains the compression gas temperature - T_C during the cycle.
(f) The regenerator gas temperature is an average of the expansion gas temperature - T_E and the compression gas temperature - T_C.
(g) The expansion space - V_E and the compression space - V_C changes following a sine curve.

Stirling Engine Analysis

Name	Symbol	Unit
Engine pressure	P	Pa
Swept volume of expansion piston or displacer piston	V_{SE}	m^3
Swept volume of compression piston or power piston	V_{SC}	m^3
Dead volume of expansion space	V_{DE}	m^3
Regenerator volume	V_R	m^3
Dead volume of compression space	V_{DC}	m^3
Expansion space momental volume	V_E	m^3
Compression space momental volume	V_C	m^3
Total momental volume	V	m^3
Total mass of working gas	m	kg
Gas constant	R	J/kgK
Expansion space gas temperature	T_H	K
Compression space gas temprature	T_C	K
Regenerator space gas temperature	T_R	K
Phase angle	dx	deg
Temperatuer ratio	t	
Swept volume ratio	v	
Dead volume ratio	X	
Engine speed	n	Hz
Indicated expansion energy	W_E	J
Indicated compression energy	W_C	J
Indicated energy	W_i	J
Indicated expansion power	L_E	W
Indicated compression power	L_C	W
Indicated power	L_i	W
Indicated efficiency	e	

Stirling Engine Analysis

Alpha-type Stirling Engine

The volumes of the expansion- and compression cylinder at a given crank angle are determined at first. The volumes are described with a crank angle - *x*. This crank angle is defined as *x*=0 when the expansion piston is located the most top position (top dead point).

The expansion volume - V_E is described in equation (2) with a swept volume of the expansion piston - V_{SE}, an expansion dead volume - V_{DE} under the condition of assumption (g).

$$V_E = \frac{V_{SE}}{2}(1-\cos x) + V_{DE} \qquad (2)$$

The compression volume - V_C is found in equation (3) with a swept volume of the compression piston - V_{SC}, a compression dead volume - V_{DC} and a phase angle - *dx*.

$$V_C = \frac{V_{SC}}{2}\{1-\cos(x-dx)\} + V_{DC} \qquad (3)$$

The total volume is calculated in equation (4).

$$V = V_E + V_R + V_C \qquad (4)$$

By the assumptions (a), (b) and (c), the total mass in the engine - *m* is calculated using the engine pressure - P, each temperature - T , each volume - V and the gas constant - R.

$$m = \frac{PV_E}{RT_E} + \frac{PV_R}{RT_R} + \frac{PV_C}{RT_C} \qquad (5)$$

Stirling Engine Analysis

The temperature ratio - t, a swept volume ratio - v and other dead volume ratios are found using the following equations.

$$t = \frac{T_C}{T_E} \qquad (6)$$

$$v = \frac{V_{SC}}{V_{SE}} \qquad (7)$$

$$X_{DE} = \frac{V_{DE}}{V_{SE}} \qquad (8)$$

$$X_{DC} = \frac{V_{DC}}{V_{SE}} \qquad (9)$$

$$X_R = \frac{V_R}{V_{SE}} \qquad (10)$$

The regenerator temperature - T_R is calculated in equation (11), by using the assumption (f).

$$T_R = \frac{T_E + T_C}{2} \qquad (11)$$

When equation (5) is changed using equation (6)-(10) and using equation (2) and (3), the total gas mass - *m* is described in the next equation.

$$m = \frac{PV_{SE}}{2RT_C}\{S - B\cos(x - a)\} \qquad (12)$$

Stirling Engine Analysis

Now;

$$a = \tan^{-1}\frac{v\sin dx}{t+\cos dx} \qquad (13)$$

$$S = t + 2tX_{DE} + \frac{4tX_R}{1+t} + v + 2X_{DC} \qquad (14)$$

$$B = \sqrt{t^2 + 2tv\cos dx + v^2} \qquad (15)$$

The engine pressure - P is defined as a next equation using equation (12).

$$P = \frac{2mRT_C}{V_{SE}\{S - B\cos(\theta - a)\}} \qquad (16)$$

The mean pressure - P_{mean} can be calculated as follows:

$$P_{mean} = \frac{1}{2\pi}\oint P dx = \frac{2mRT_C}{V_{SE}\sqrt{S^2 - B^2}} \qquad (17)$$

c is defined in the next equation.

$$c = \frac{B}{S} \qquad (18)$$

Stirling Engine Analysis

As a result, the engine pressure - P, based the mean engine pressure - P_{mean} is calculated in equation (19).

$$P = \frac{P_{mean}\sqrt{S^2 - B^2}}{S - B\cos(x-a)} = \frac{P_{mean}\sqrt{1-c^2}}{1 - c\cos(x-a)} \qquad (19)$$

On the other hand, in the case of equation (16), when cos(x-a)=-1, the engine pressure - P becomes the minimum pressure - P_{min}, the next equation is introduced.

$$P_{\min} = \frac{2mRT_C}{V_{SE}(S+B)} \qquad (20)$$

Therefore, the engine pressure - P, based the minimum pressure - P_{min} is described in equation (21).

$$P = \frac{P_{\min}(1-c)}{1 - c\cos(x-a)} \qquad (21)$$

Similarly, when cos(x-a)=1, the engine pressure - P becomes the maximum pressure - P_{max}. The following equation is introduced.

$$P = \frac{P_{\max}(1-c)}{1 - c\cos(x-a)} \qquad (22)$$

The P-V diagram of Alpha-type Stirling engine can be made with above equations.

Stirling Engine Analysis

3. INDICATED ENERGY, POWER AND EFFICIENCY

The indicated energy (area of the P-V diagram) in the expansion and compression space can be calculated as an analytical solutions with use of the above coefficients. The indicated energy in the expansion space (indicated expansion energy) - W_E(J), based on the mean pressure - P_{mean}, the minimum pressure - P_{min} and the maximum pressure - P_{max} are described in the following equations.

$$W_E = \oint P dV_E = \frac{P_{mean} V_{SE} \pi c \sin a}{1+\sqrt{1-c^2}} = \frac{P_{\max} V_{SE} \pi c \sin a}{1+\sqrt{1-c^2}} \frac{\sqrt{1-c}}{\sqrt{1+c}} \quad (23)$$

The indicated energy in the compression space (indicated compression energy) - W_C(J) are described in the next equations.

$$W_C = \oint P dV_C = \frac{P_{mean} V_{SE} \pi c t \sin a}{1+\sqrt{1-c^2}} = \frac{P_{\max} V_{SE} \pi c t \sin a}{1+\sqrt{1-c^2}} \frac{\sqrt{1-c}}{\sqrt{1+c}} \quad (24)$$

The indicated energy per one cycle of this engine - Wi(J) is

$$W_i = W_E + W_C = \frac{P_{\max} V_{SE} \pi c (1-t) \sin a}{1+\sqrt{1-c^2}} \frac{\sqrt{1-c}}{\sqrt{1+c}} \quad (25)$$

Stirling Engine Analysis

The indicated expansion power - L_E(W), the indicated compression power - L_C(W) and the indicated power of this engine - L_i(W) are defined in the following equations, using the engine speed per one second , n(rps, Hz).

$$L_E = W_E n \quad L_C = W_C n \quad L_i = W_i n \tag{26}$$

The indicated expansion energy - W_E found equation (23) means an input heat from a heat source to the engine. The indicated compression energy - W_c calculated by equation (24) means a reject heat from the engine to cooling water or air. Then the thermal efficiency of the engine - η is calculated in the next equation.

$$\eta = \frac{W_i}{W_E} = 1 - t = 1 - \frac{T_c}{T_E} \tag{27}$$

This efficiency equals that of a Cornot cycle which is the most highest efficiency in every thermal engine.

The steady heat transfer from a hot to a cold environment, the time rate of heat transfer $\dot{q}$ may be represented by

$$\dot{q} = hA(T_H - T_C)$$

Where A is the surface area of the material that separates the two environments and across which the heat flows and *h* is the heat transfer coefficient, a property of the material separating the two environments.

Homework Problem

Due: October 4, 2005

Make a P-V diagram and calculate the indicated power of an Alpha-type Stirling engine under following conditions. Swept volume of an expansion piston: 1 cm^3, swept volume of a compression piston: 1 cm^3, dead volume of the expansion space: 0.25 cm^3, dead volume of the compression space: 0.25 cm^3, regenerator volume: 0.25 cm^3, phase angle: 90^o, mean pressure: 105 kPa, expansion gas temperature: 500^{o}C, compression gas temperature: 50^{o}C, engine speed: 2000 rpm.

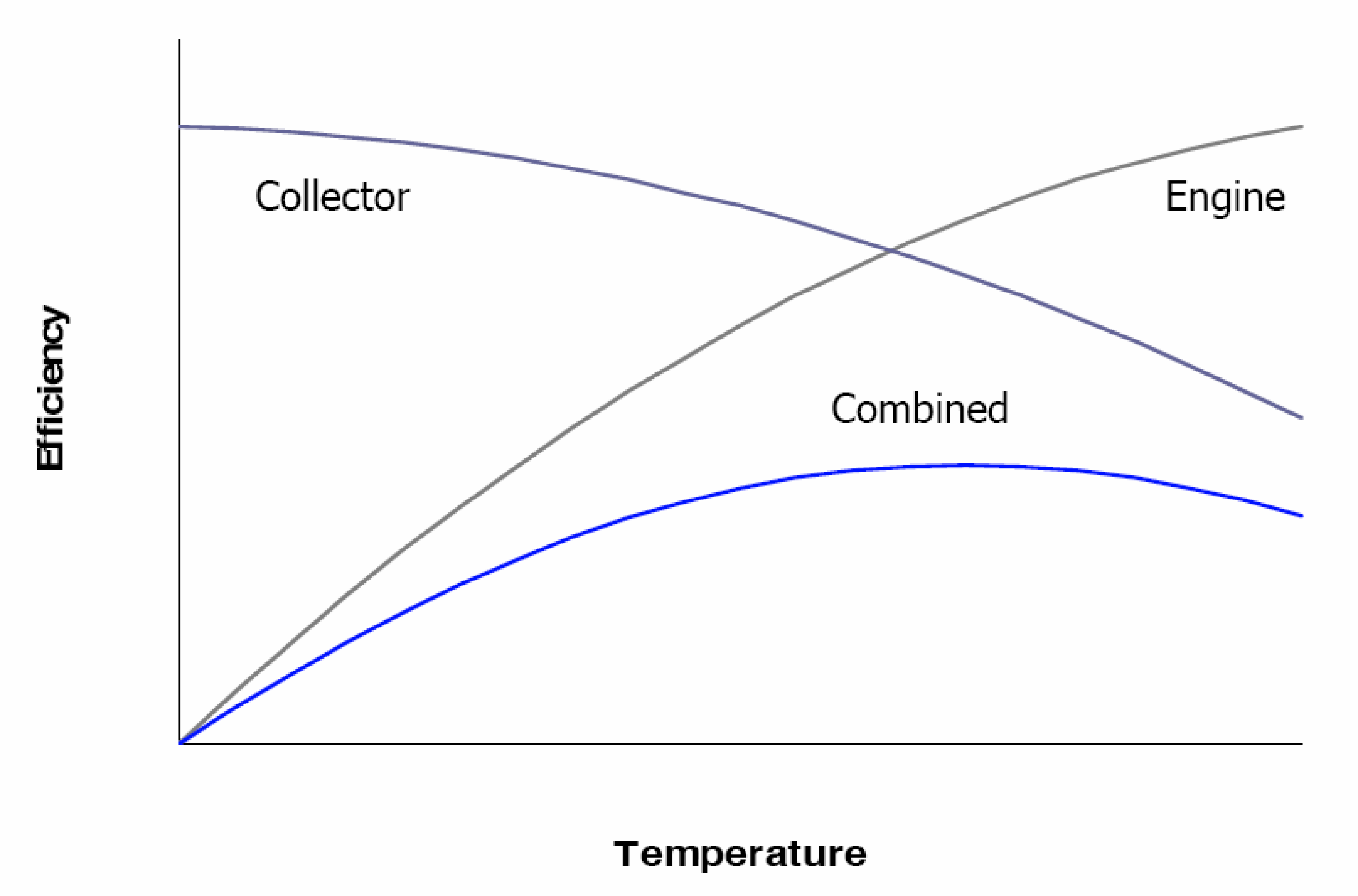
http://travel.howstuffworks.com/framed.htm?parent=stirling-engine.htm&url=http://www.bekkoame.ne.jp/~khirata/

Solar Dish Stirling System

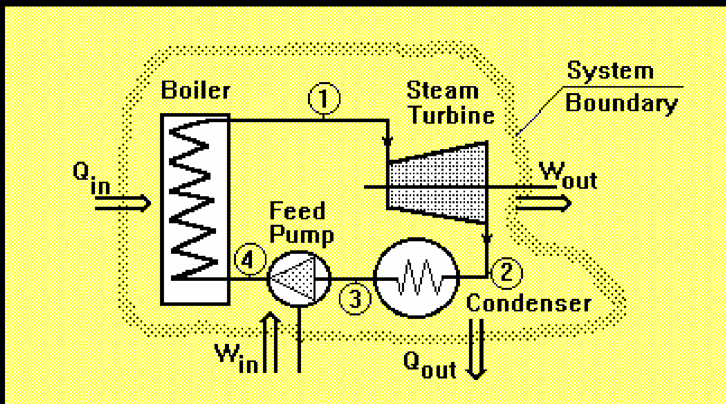
Advnco/Vanguard 25 kW dish/Stirling system installed at Rancho Mirage, California.

The Vanguard concentrator is approximately 11 meters in diameter and made of 366 mirror facets, each facet measures 18 by 24 inches. The engine used is a United Stirling AB (USAB) Model 4-95 Mark II driving a commercial 480 volt/ac 60-Hz alternator.

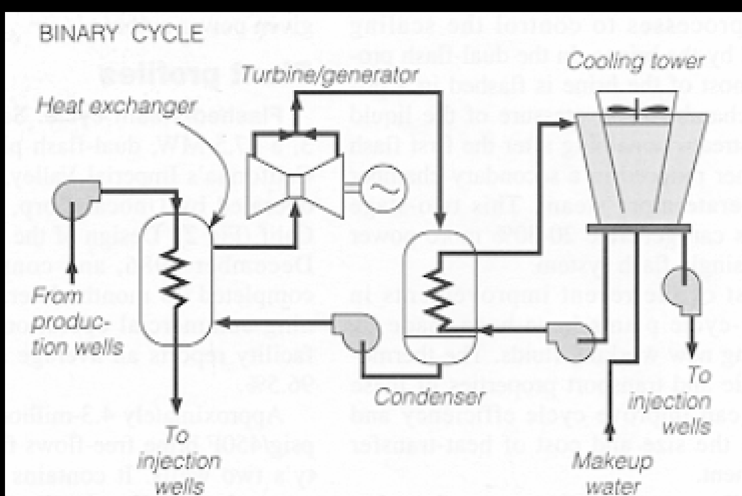
Solar Dish Stirling System Efficiency



Rankine Cycle Engine

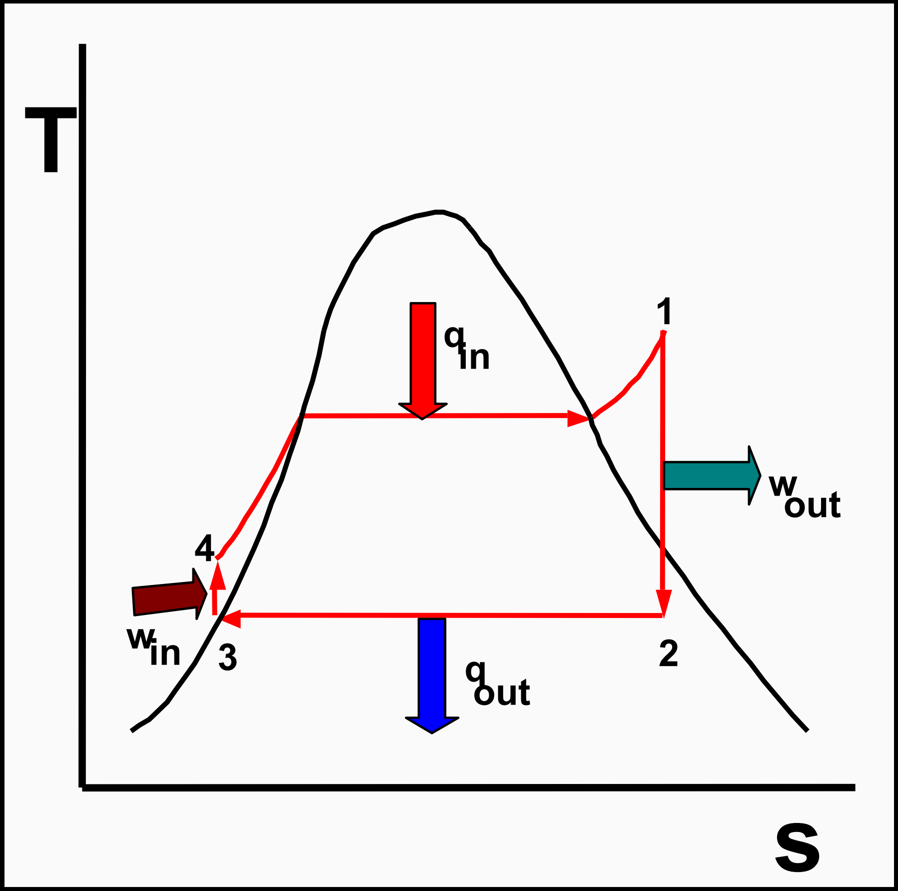


The Rankine cycle based engines are low maintenance alternative in renewable energy applications. The engine uses a heat source, such as concentrated solar radiation, to provide energy to a fluid in a closed cycle. This, in turn, drives a turbine which can be used to produce electricity. This is so called solar Rankine cycle engine.



Geothermal energy application

Rankine Cycle Efficiency

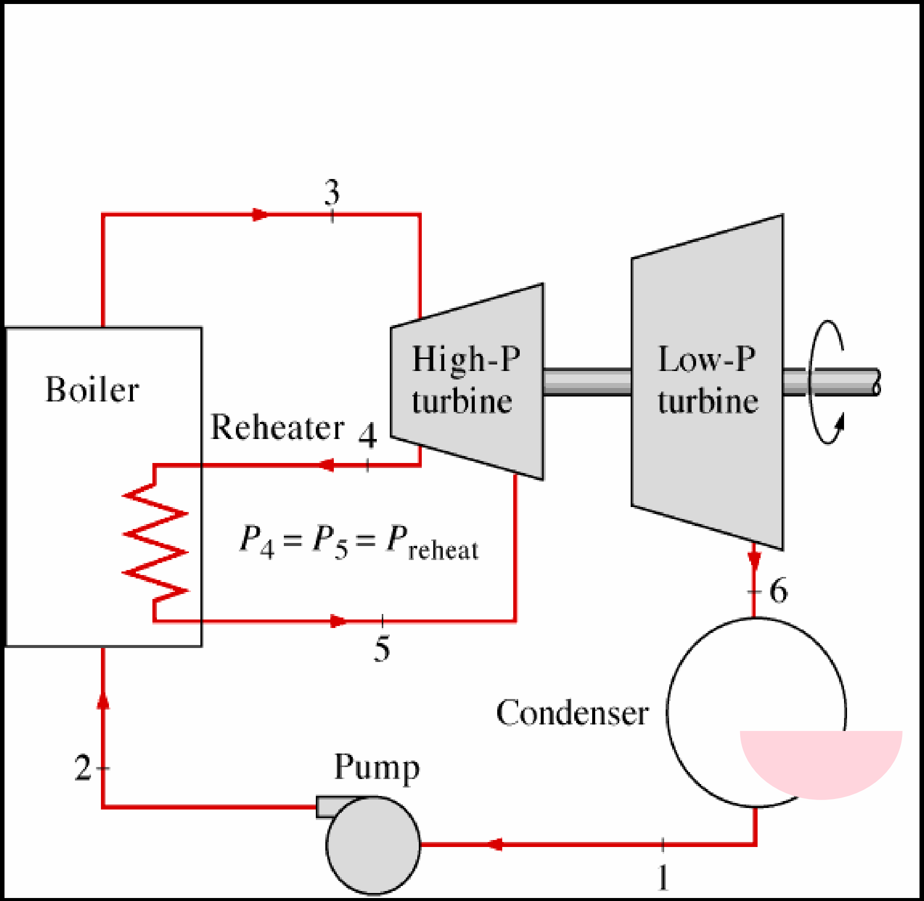


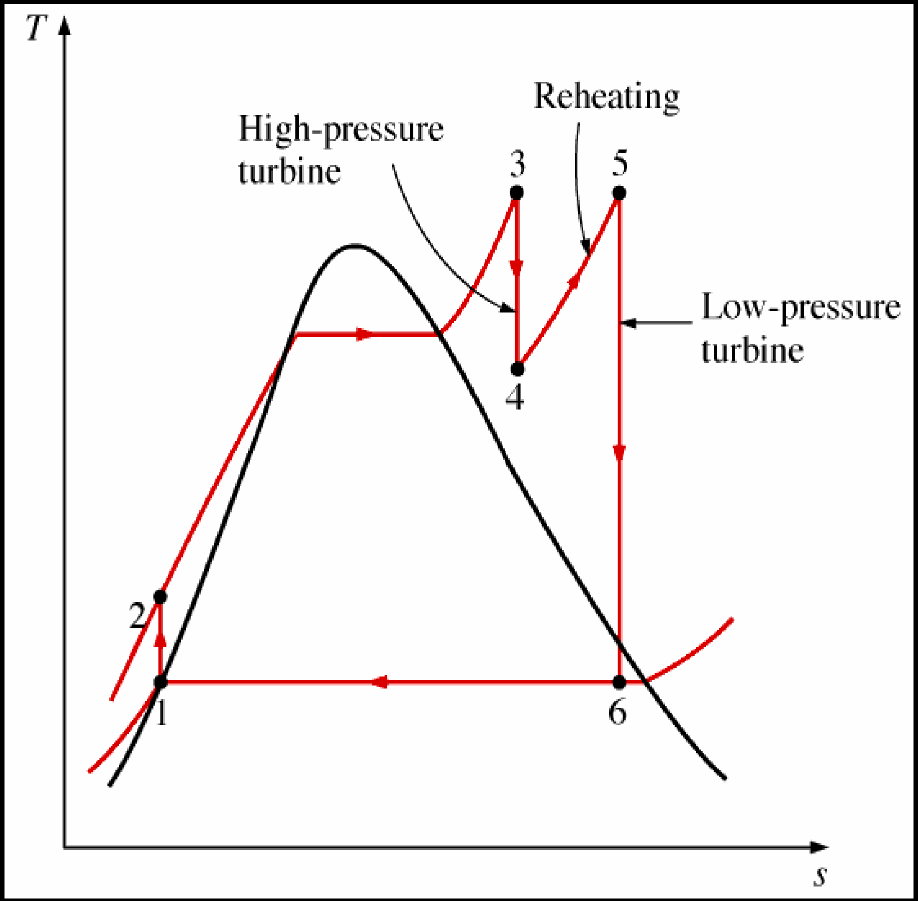
$$\eta = \frac{w_{turbine} - w_{pump}}{q_{in}}$$

$$\eta_{th} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

Unlike Carnot cycle, the thermodynamic efficiency depends explicitly upon the working fluid properties.

Ideal Reheat Rankine Cycle

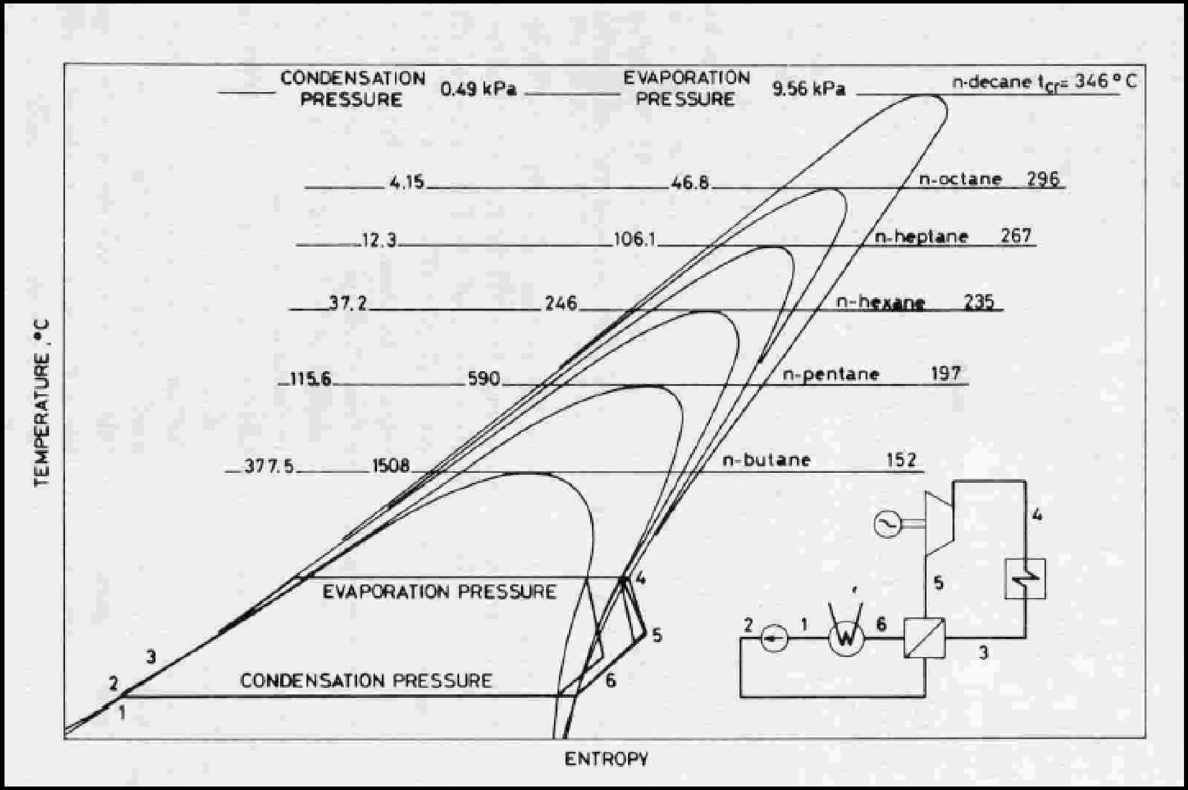




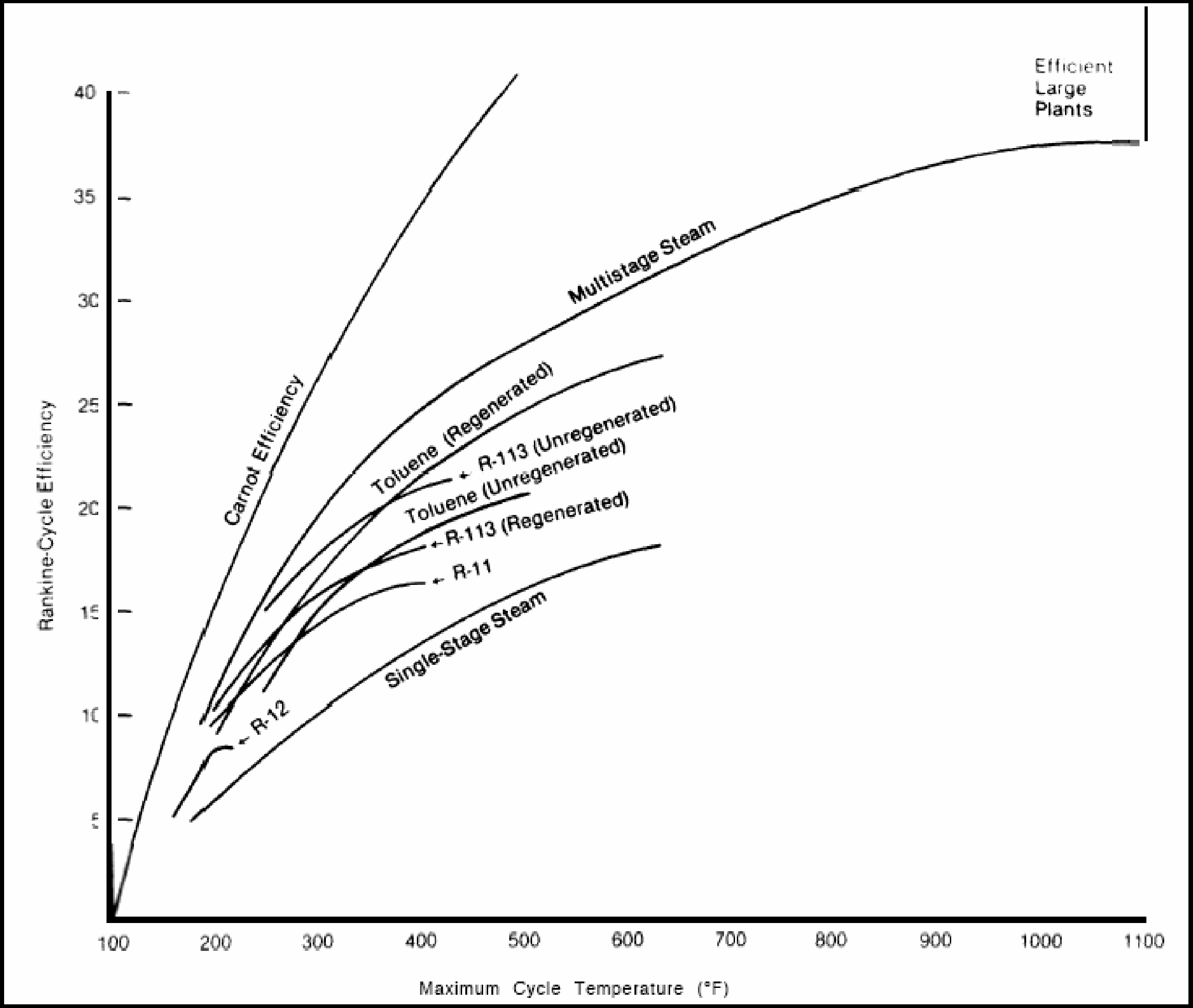
Organic Rankine Cycle

The ORC technology is based on the Rankine cycle with the difference that instead of water a high molecular mass organic fluid as working medium is used. The selected working fluids allow to exploit efficiently low temperature heat sources (70 to 400°C) to produce electricity.

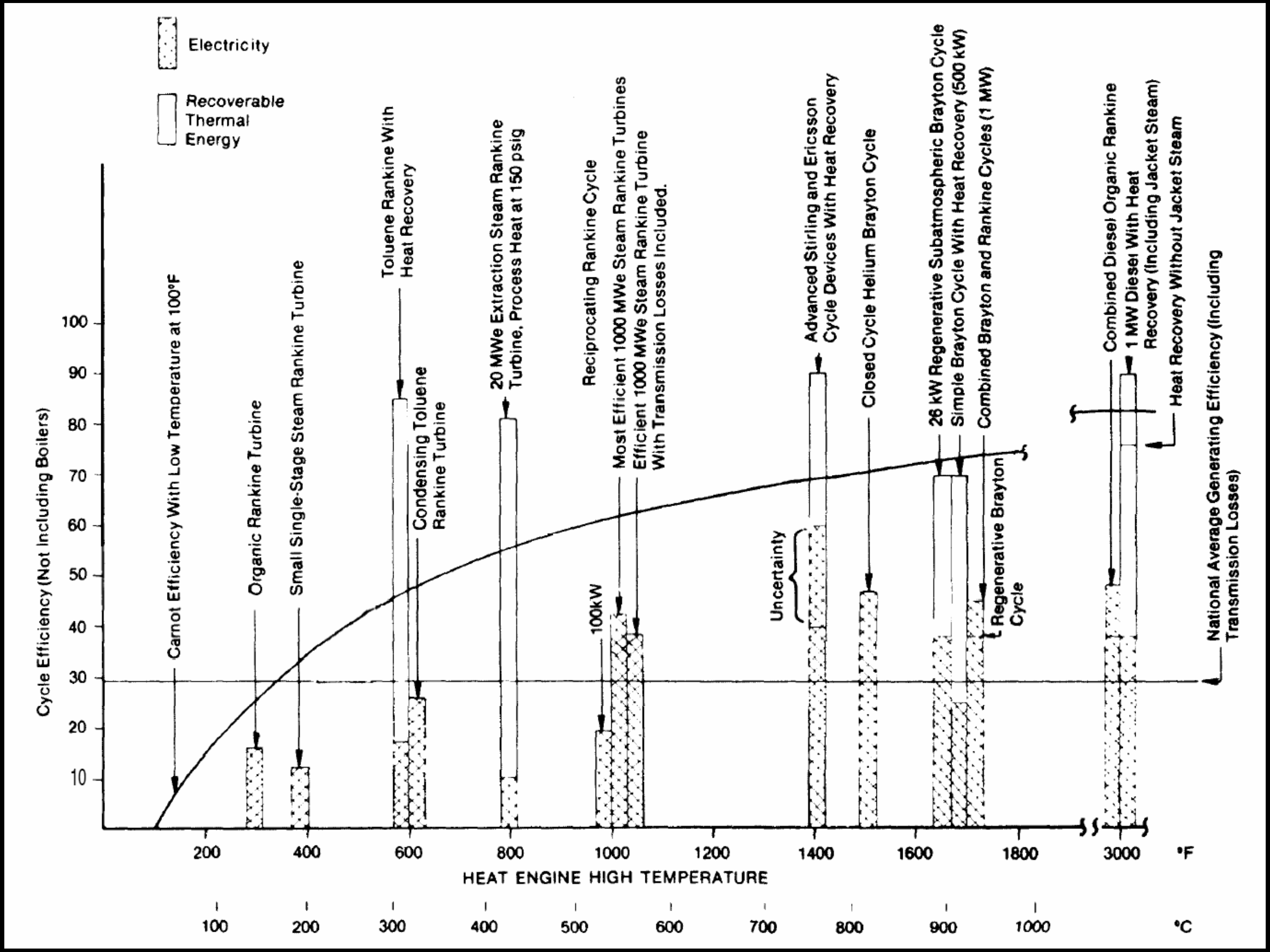
The organic fluid is vaporized by application of heat source in the evaporator. The organic fluid vapor expands and is then condensed in a heat exchanger. The condensate is pumped back to the evaporator thus closing the thermodynamic cycle.



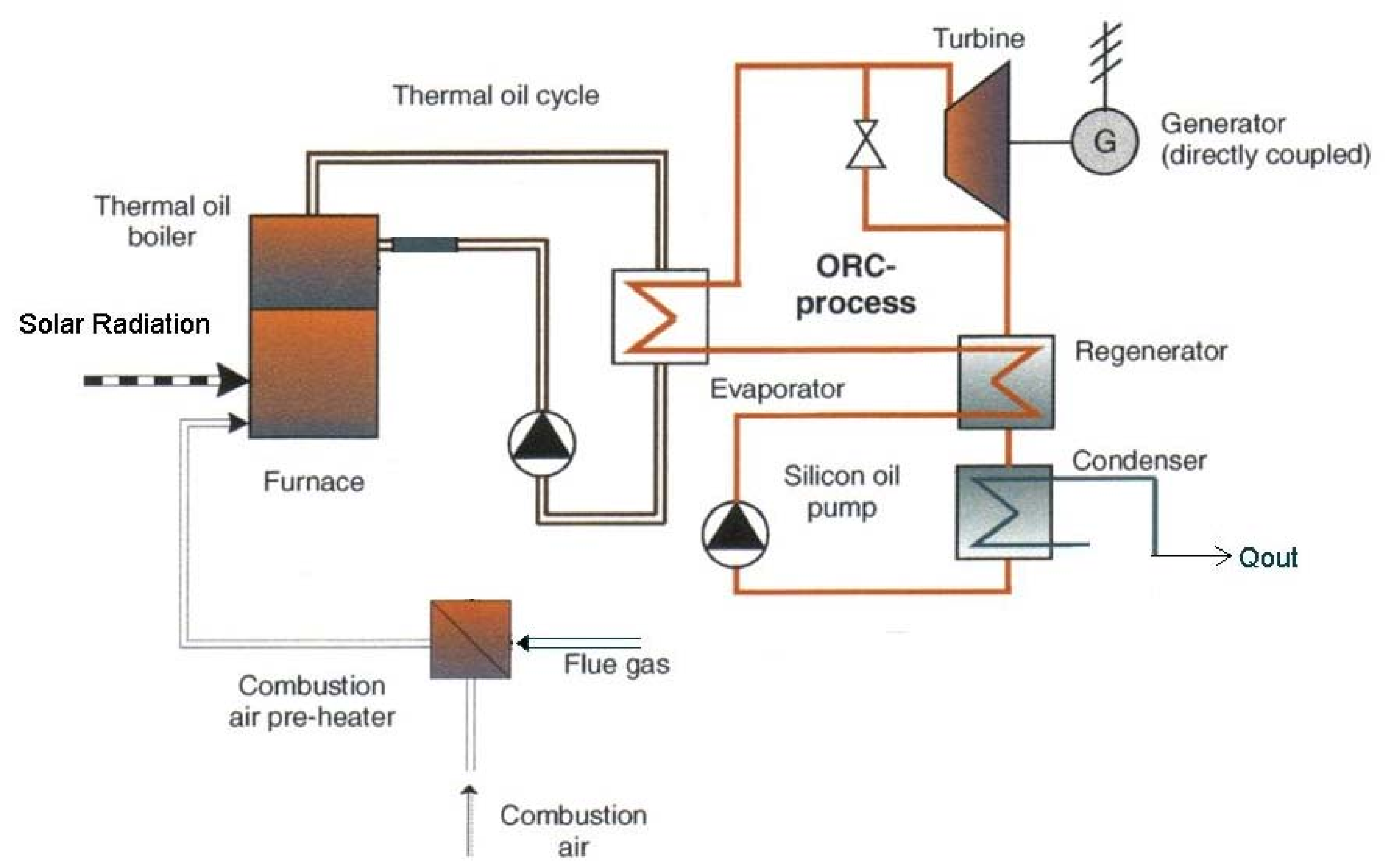
Temperature Dependence of Rankine Cycle Devices



Cycle efficiencies with Heat engines



Organic Rankine Cycle



Externally Heated Systems

$$\eta_C = 1 - \frac{T_c}{T_h}$$

$$\eta_i = 1 - \frac{T_c}{T_h - T_h'} \ln\left(\frac{T_h}{T_h'}\right)$$

In many cases, heat will be available only in the form of a heated fluid which cools as energy is extracted from a fluid which cools from T_h to T_h' while giving up heat to the engine. The maximum efficiency is given by the “ideal” efficiency (η_i) , where

Cogeneration

Providing electricity and thermal energy to improve the efficiency of the energy conversion system

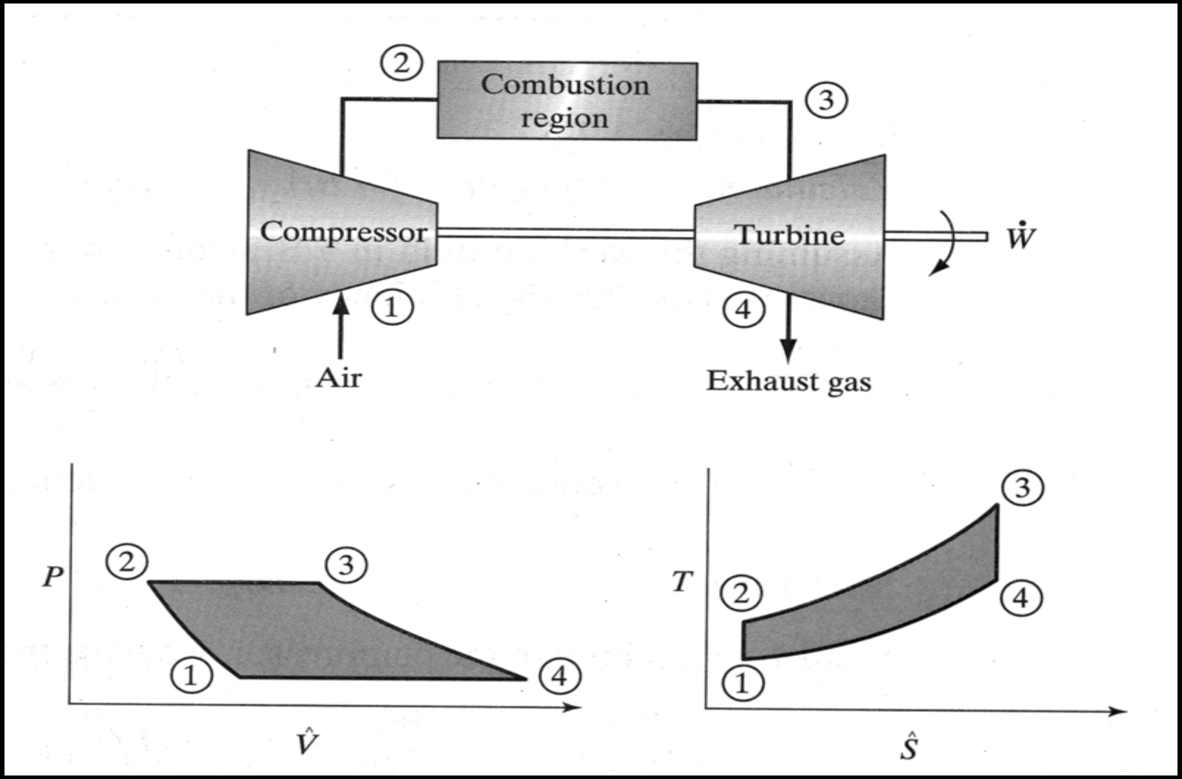
1. Generate electricity at the maximum possible efficiency and produce the thermal energy with a separate collector.
2. Generate electricity at the maximum possible efficiency and use a heat engine that would reject heat at the lowest temperature. (generally defines the maximum efficiency)
3. Use a heat engine that would reject heat at high enough temperature to be useful for thermal processes, such as space or water heating.

Thermodynamics Fundamentals for Energy Conversion Systems

(Continued)

The study of the laws that govern the conversion of energy from one form to the other

Open Brayton Power Cycle



Joule or Brayton cycles are used either in open or closed systems in heat engines or in power plants exclusively with gas turbines. The Brayton cycle is also known as the gas turbine cycle since it uses gases (other than steam) which can be compressed but not liquefied by a condenser.

Open Brayton Power Cycle

The air-standard Brayton cycle is an ideal cycle that approximates the processes incorporated within the standard gas-turbine engine. In the following description of the ideal Brayton cycle, the initial state is taken where atmospheric pressure air enters the inlet of a steady flow compressor. This cycle is shown for constant specific heats on P-v, and T-s diagrams.

Process 1 - 2: an isentropic compression of atmospheric air from the inlet to the compressor to the maximum pressure in the cycle,
Process 2-3: a constant-pressure combustion process (heat addition),
Process 3-4: an isentropic expansion of the products of combustion from the inlet to the turbine to the exhaust of the turbine at atmospheric pressure,
Process 4-1: a constant-pressure heat rejection process until the temperature returns to initial conditions.

The thermal efficiency of this cycle is found as the net work delivered by the cycle divided by the heat added to the working substance. From this definition of the cycle thermal efficiency, we may write:

$$\eta = \frac{W_{net}}{Q_{added}} = 1 - \frac{Q_{rejected}}{Q_{added}}$$

Open Brayton Power Cycle

Since the constant pressure heat rejection is equal to the change of enthalpy in process from state 4 to state 1, and the heat added in a constant pressure process from state 2 to state 3 is the change of enthalpy between these two states, we may write for the case of constant specific heats:

$$\eta = 1 - \frac{\left(\frac{T_4}{T_2} - \frac{T_1}{T_2}\right)}{\frac{T_3}{T_2} - 1}$$

Note that the process from state 1 to state 2 is an isentropic compression and the process from state 3 to state 4 is an isentropic expansion, and that P3 = P2 and that P4 = P1. Hence, we may write:

$$\frac{T_2}{T_1} = \frac{p_2}{p_1}^{\frac{(\gamma-1)}{\gamma}} = \frac{p_3}{p_4}^{\frac{(\gamma-1)}{\gamma}} = \frac{T_3}{T_4}$$

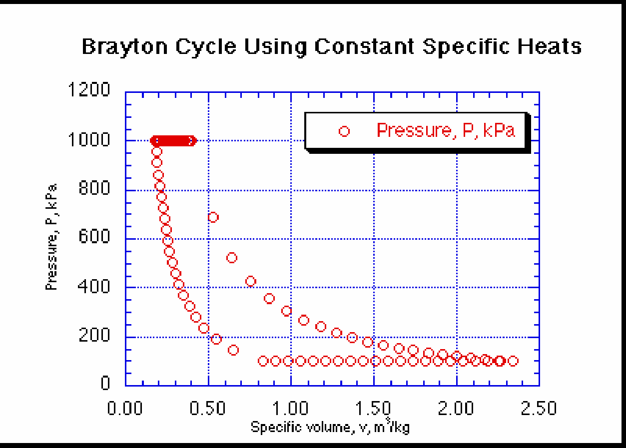
where γ is the ratio of specific heats. Canceling through the appropriate terms yields an expression for the ideal Brayton cycle thermal efficiency for constant specific heats as:

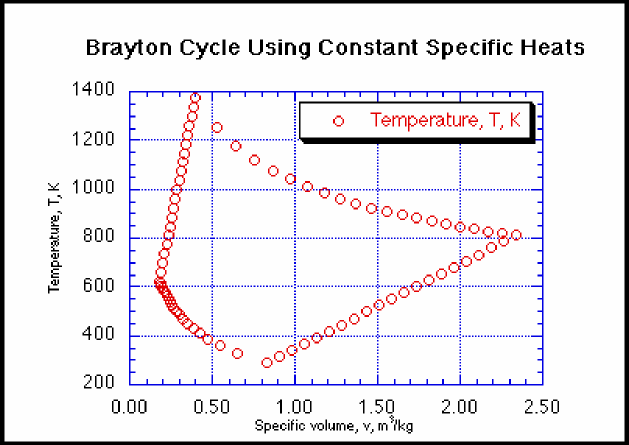
$$\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{p_1}{p_2}^{\frac{\gamma}{(\gamma-1)}}$$

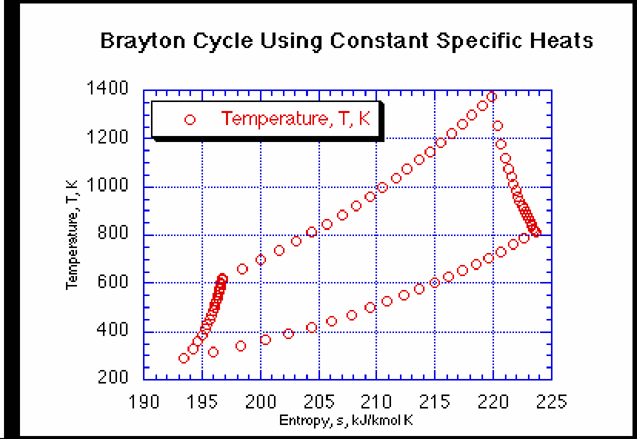
In this expression, the ratio P_2 / P_1, is the pressure ratio for the cycle.

Open Brayton Power Cycle

The following figures were produced using an ideal Brayton cycle with constant specific heats, with the working substance consisting a mixture of oxygen and nitrogen in the ratio of 1.0 kmol of O_2 to 3.773 kmols of N_2. The initial pressure in the cycle is 100.0 kPa, the initial temperature is 288.15 K, and the maximum temperature is taken as 1373.15 K. The pressure ratio for the cycle is 10.0. The adiabatic compressor efficiency is 80.0% and the adiabatic turbine efficiency is 85.0%. The results indicate a cycle thermal efficiency of 0.3031 and a cycle back work ratio of 0.5950.

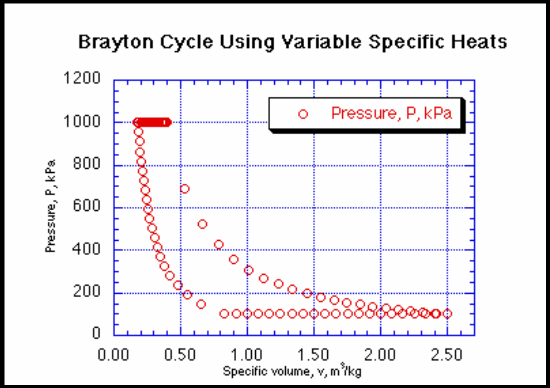


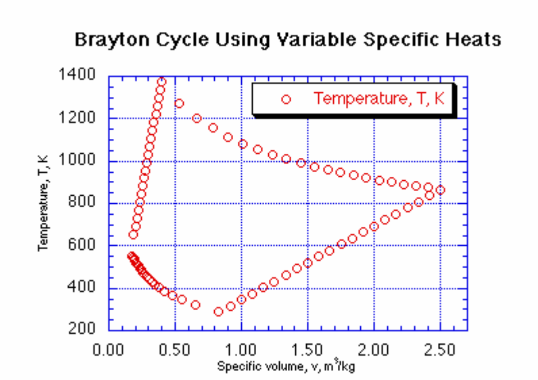


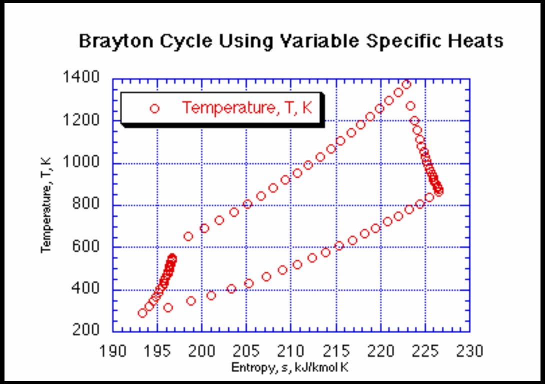


Open Brayton Power Cycle

The following figures were produced using an ideal Brayton cycle with variable specific heats, with the working substance again consisting a mixture of oxygen and nitrogen in the ratio of 1.0 kmol of O_2 to 3.773 kmols of N_2 The initial pressure in the cycle is 100.0 kPa, the initial temperature is 288.15 K, and the maximum temperature is again taken as 1373.15 K. The adiabatic compressor efficiency is 80.0% and the adiabatic turbine efficiency is 85.0%. The pressure ratio for the cycle is 10.0. The results indicate a cycle thermal efficiency of 0.2934 and a cycle back work ratio of 0.57 . Notice that the values of adiabatic compressor and turbine efficiencies have a much greater effect on the calculated values of cycle thermal efficiency than does the assumption of constant specific heats..

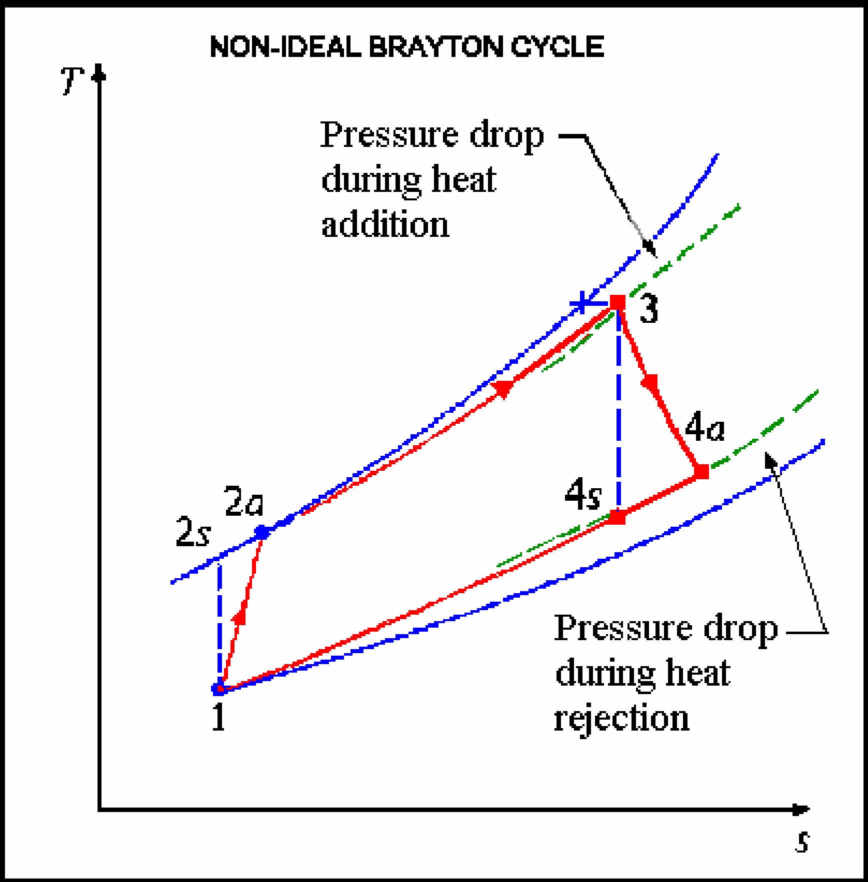






Ref: Van Wylen, G. J., Sonntag, R. E., and Borgnakke, C., "Fundamentals of Classical Thermodynamics," Fourth Edition, John Wiley & Sons, Inc., New York, 1994.

Open Brayton Cycle



Additional Equations:

Compressor:

$$\eta_c = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

where η_c is the adiabatic compressor efficiency h_{2s} is the state reached by isentropic compression from state 1, and h_{2a} is the actual state of the gas leaving the compressor.

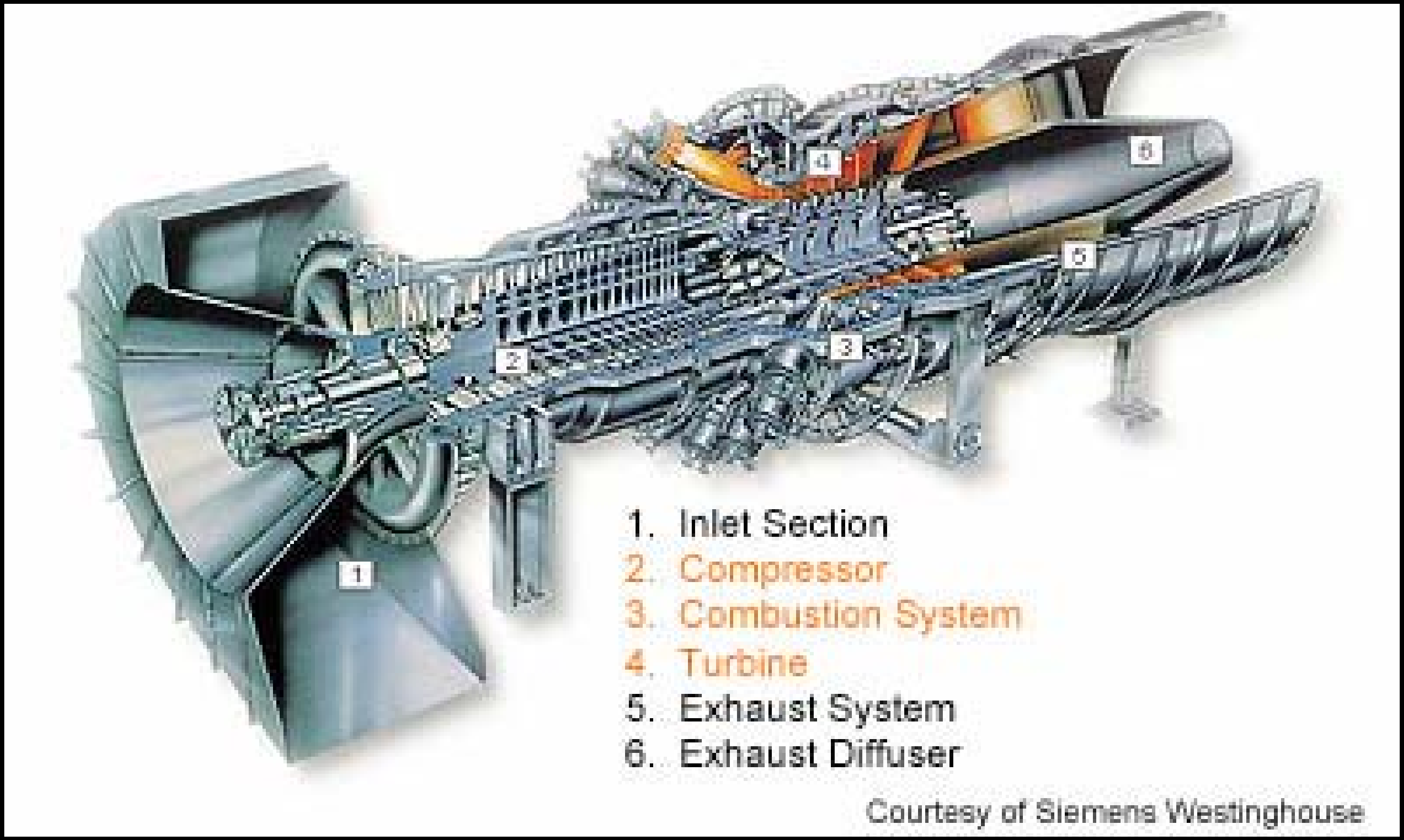
Turbine:

$$\eta_t = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

Where η_t is the turbine efficiency, h_{4s} is the state reached by isentropic expansion from state 3, and h_{4a} is the actual state of the gas leaving the turbine.

The pressure drops, P_2 - P_3 and P_4 - P_1 are usually expressed as percentages of the pressures (P_2 and P_4) entering the heat exchangers.

Gas Turbine


1
2
3
4
5
6
1. Inlet Section
2. Compressor
3. Combustion System
4. Turbine
5. Exhaust System
6. Exhaust Diffuser
Courtesy of Siemens Westinghouse

Gas Turbine

- **The compressor** which draws air into the engine, pressurizes it, and feeds it to the combustion chamber literally at speeds of hundreds of miles per hour.

- **The combustion system**, typically made up of a ring of fuel injectors that inject a steady stream of fuel (e.g., natural gas) into the combustion chamber where it mixes with the air. The mixture is burned at temperatures of more than 2000 degrees. The combustion produces a high temperature, high pressure gas stream that enters and expands through the turbine section.

- **The turbine** is an intricate array of alternate stationary and rotating aerofoil-section blades. As hot combustion gas expands through the turbine, it spins the rotating blades. The rotating blades perform a dual function: they drive the compressor to draw more pressurized air into the combustion section, and they spin a generator to produce electricity.

Gas Turbine

- Land based gas turbines are of two types: (1) heavy frame engines and (2) aeroderivative engines. Heavy frame engines are characterized by lower compression ratios (typically below 15) and tend to be physically large. Aeroderivative engines are derived from jet engines, as the name implies, and operate at very high compression ratios (typically in excess of 30). Aeroderivative engines tend to be very compact.

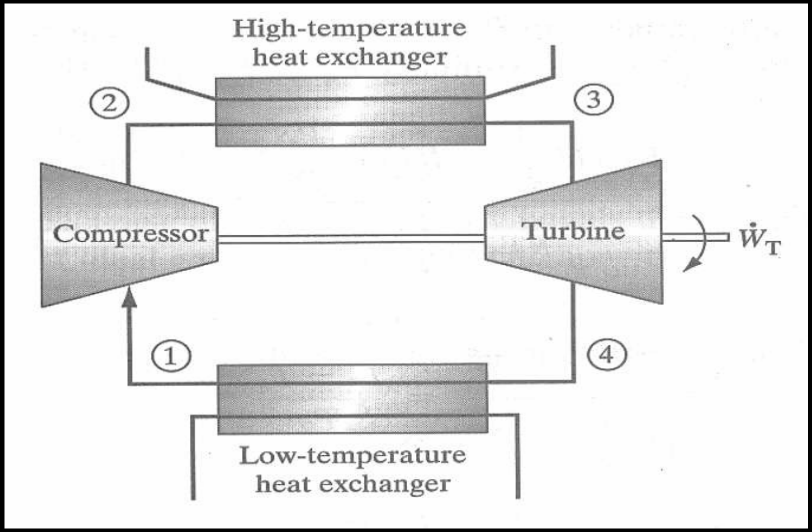
- One key to a turbine's fuel-to-energy efficiency is the temperature at which it operates. Higher temperatures generally mean higher efficiencies which, in turn, can lead to more economical operation. Gas flowing through a typical power plant turbine can be as hot as 2300 degrees F, but some of the critical metals in the turbine can withstand temperatures only as hot as 1500 to 1700 degrees F. Therefore air from the compressor is used for cooling key turbine components; however, the requirement for cooling the turbine limits the ultimate thermal efficiency.

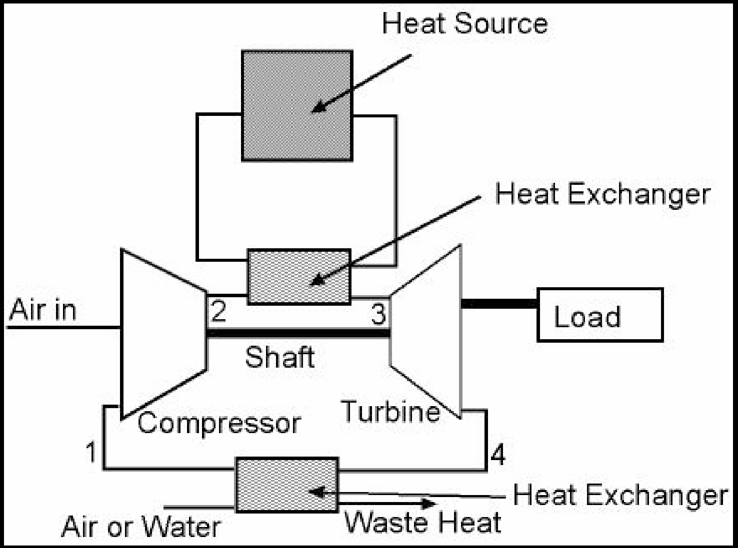
Gas Turbine

- To boost efficiency is to install a recuperator or waste heat boiler onto the turbine's exhaust. A recuperator captures waste heat in the turbine exhaust system to preheat the compressor discharge air before it enters the combustion chamber. A waste heat boiler generates steam by capturing heat from the turbine exhaust. These boilers are also known as heat recovery steam generators (HRSG). High-pressure steam from these boilers can be used to generate additional electric power with steam turbines, a configuration called a combined cycle.

- A simple cycle gas turbine can achieve energy conversion efficiencies ranging between 20 and 35 percent. With the higher temperatures achieved in the turbine (2600^{o}F), future gas turbine combined cycle plants are likely to achieve efficiencies of 60 percent or more. When waste heat is captured from these systems for heating or industrial purposes, the overall energy cycle efficiency could approach 80 percent.

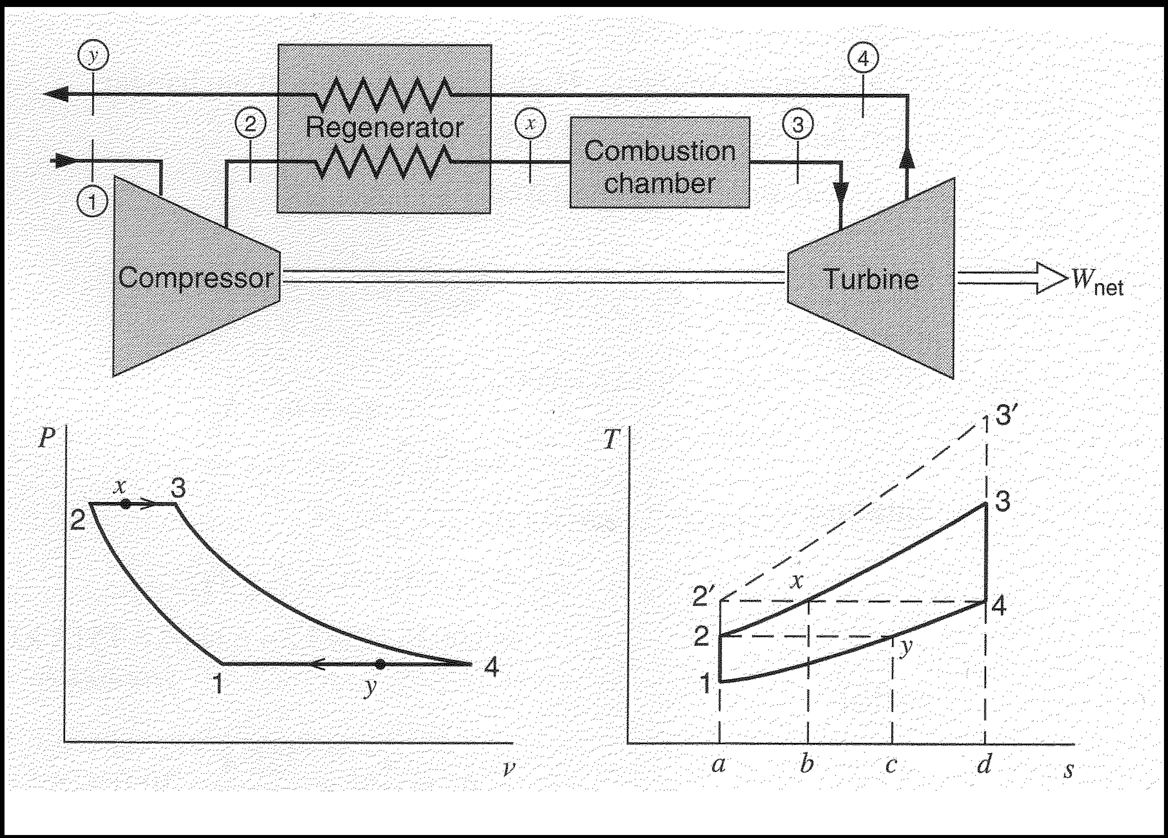
Closed Brayton Power Cycle





The additional complexity of this Brayton cycle model is a function of including a closed circuit for fluid involved in the combustion or heating process. In a power plant, such a fluid could be gas heated from combustion of oil, coal, or natural gas or from nuclear fission. In engines, the fluid would most likely be the gas produced via combustion. The resulting high pressure fluid does not expand through the turbine itself. Instead, the heat exchanger represented by the gray box transmits most of the heat by conduction and convection, although some efficiency losses are incurred. Another heat exchanger cools the gaseous working fluid after it passes through the turbine. This system is closed because circuits of fluid are employed; the fluid which expands through the turbine is not merely expelled as exhaust. It represents models integrated in power plant design. In a Brayton cycle, the working fluid is a gas which remains a gas throughout the cycle and is not condensed to a liquid.

Brayton Cycle - Regeneration



The exhaust gases leaving the turbine in state 4 is higher than the temperature of the gas leaving the compressor. Therefore heat can be transferred from the exhaust gases to the high pressure gas leaving the Compressor using a counterflow heat Exchanger, known as regenerator.

Brayton Cycle - Regenerator

The efficiency of the cycle with regeneration is found as follows:

$$\eta_{th} = \frac{w_{net}}{q_H} = \frac{w_t - w_c}{q_H}$$

$$q_H = C_p(T_3 - T_x)$$

$$w_t = C_p(T_3 - T_4)$$

For an ideal regenerator, $T_4 = T_x$ and therefore $q_H = w_t$, Consequently

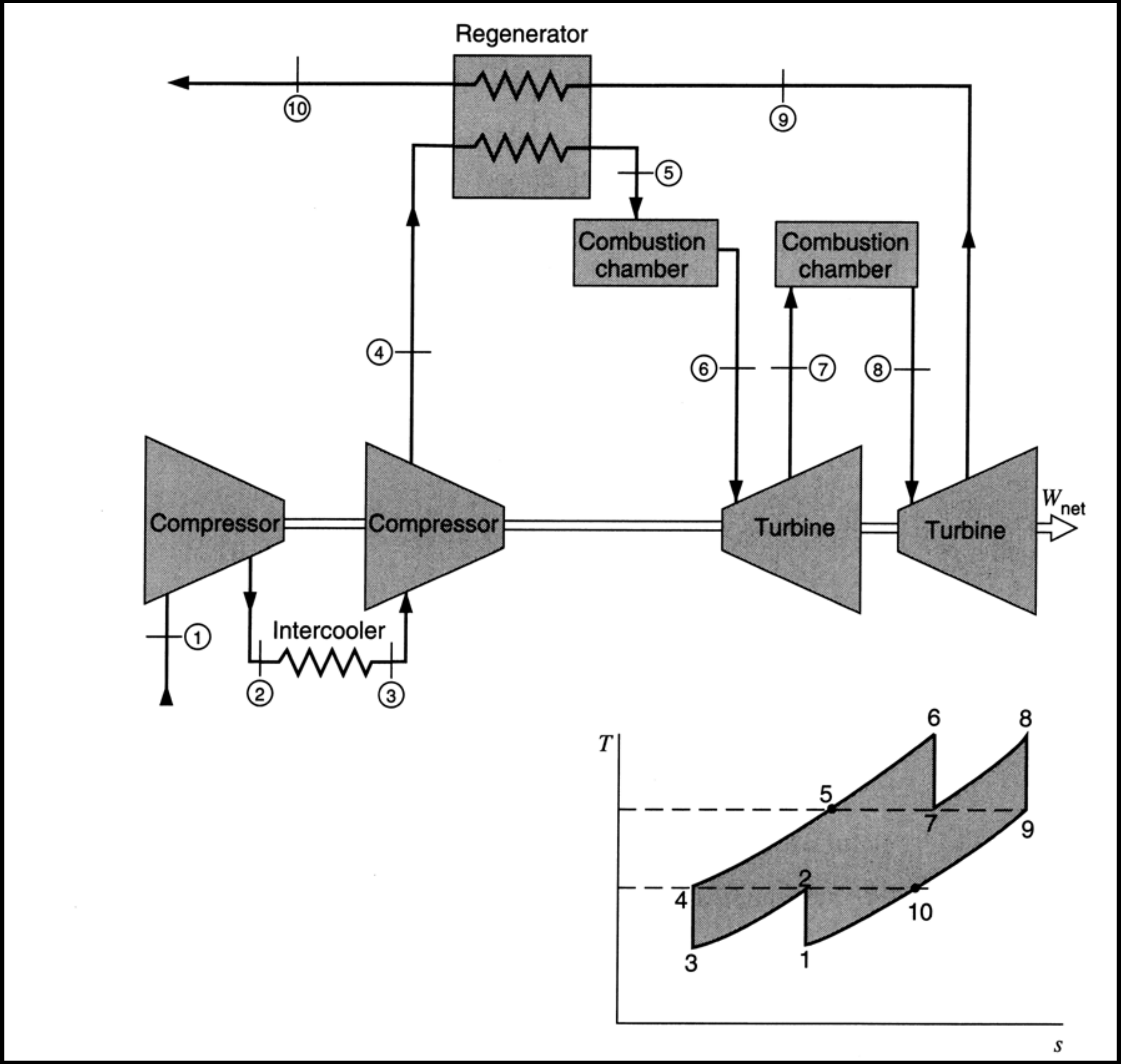
$$\eta_{th} = 1 - \frac{w_c}{w_t} = 1 - \frac{C_p(T_2 - T_1)}{C_p(T_3 - T_4)} = 1 - \frac{T_1}{T_2}\left[\frac{P_2}{P_1}\right]^{\frac{(\gamma-1)}{\gamma}}$$

The high pressure gas leave the generator at temperature $T_x' = T_4$.

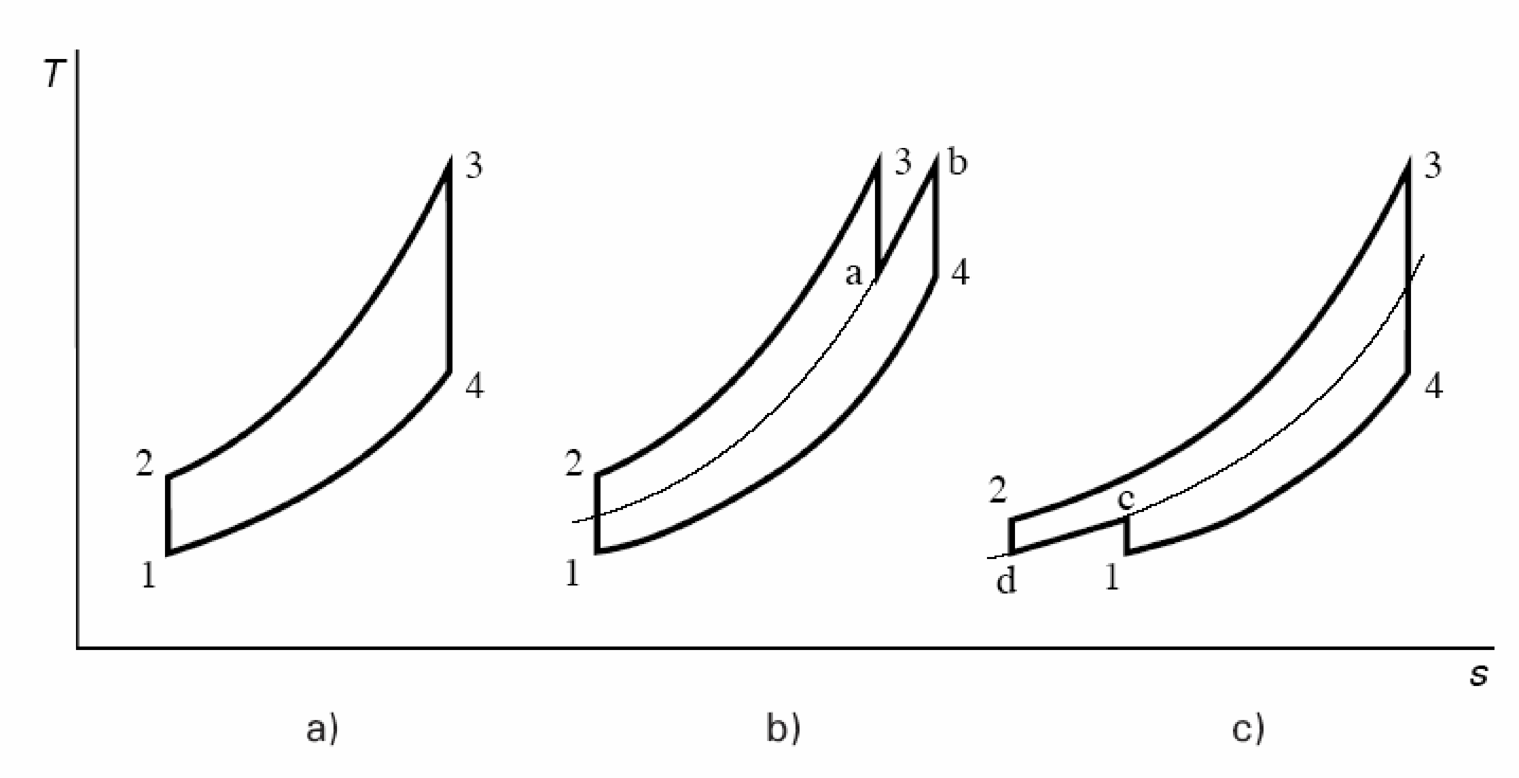
Therefore the regenerator efficiency is defined by

$$\eta_{reg} = \frac{(h_x - h_2)}{(h_x' - h_2)}$$

Brayton Cycle with Regeneration and Intercooling

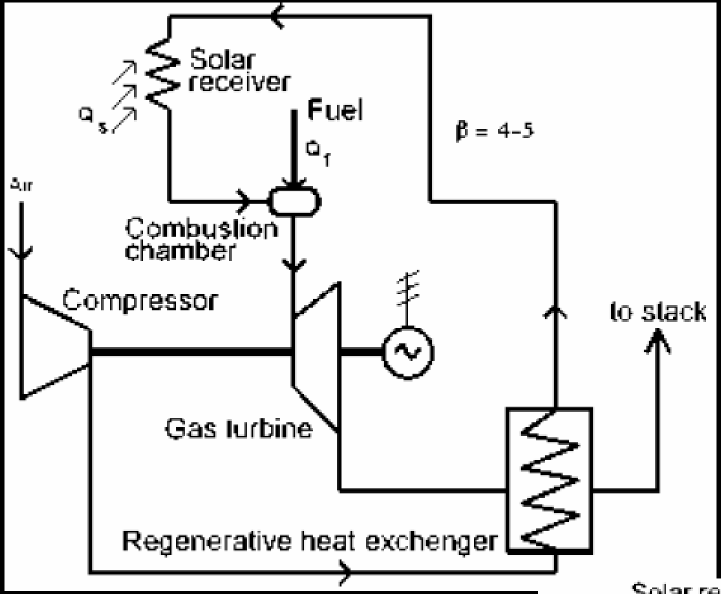


Brayton Cycles

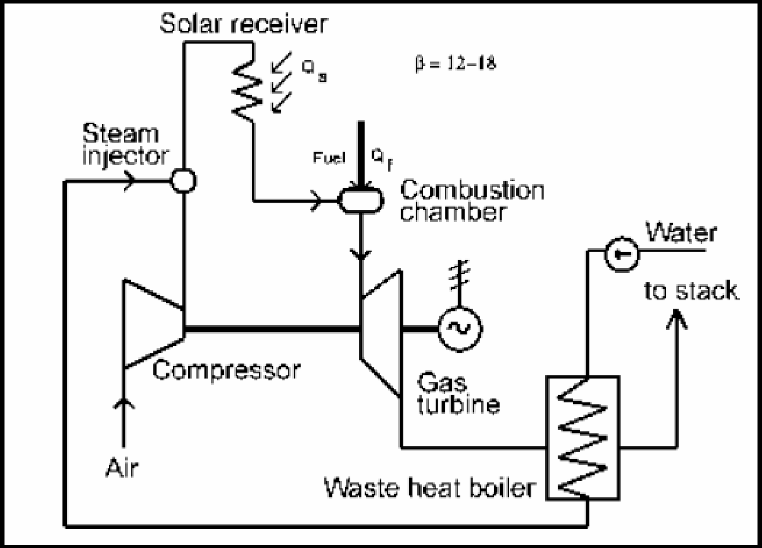


a) Basic cycle; b) with reheat; c) with intercooling

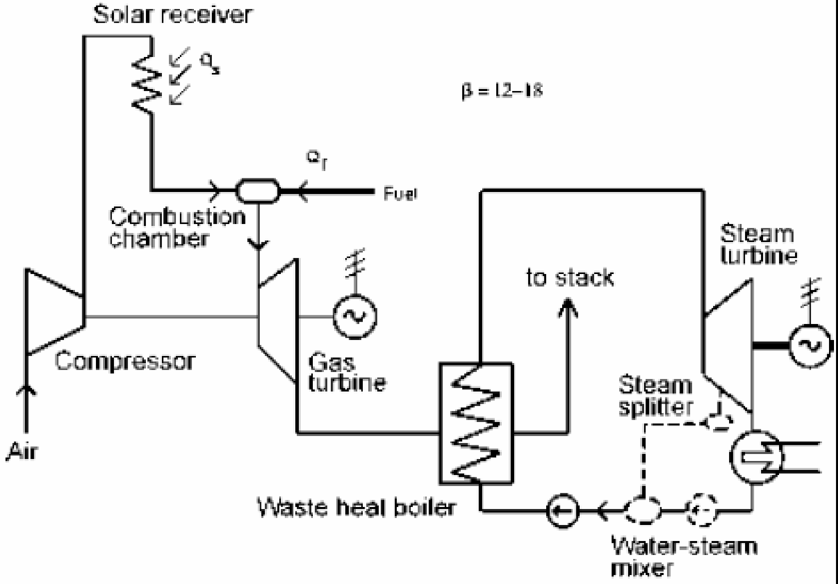
Brayton Cycles



Regenerative Brayton Cycle (RBC)

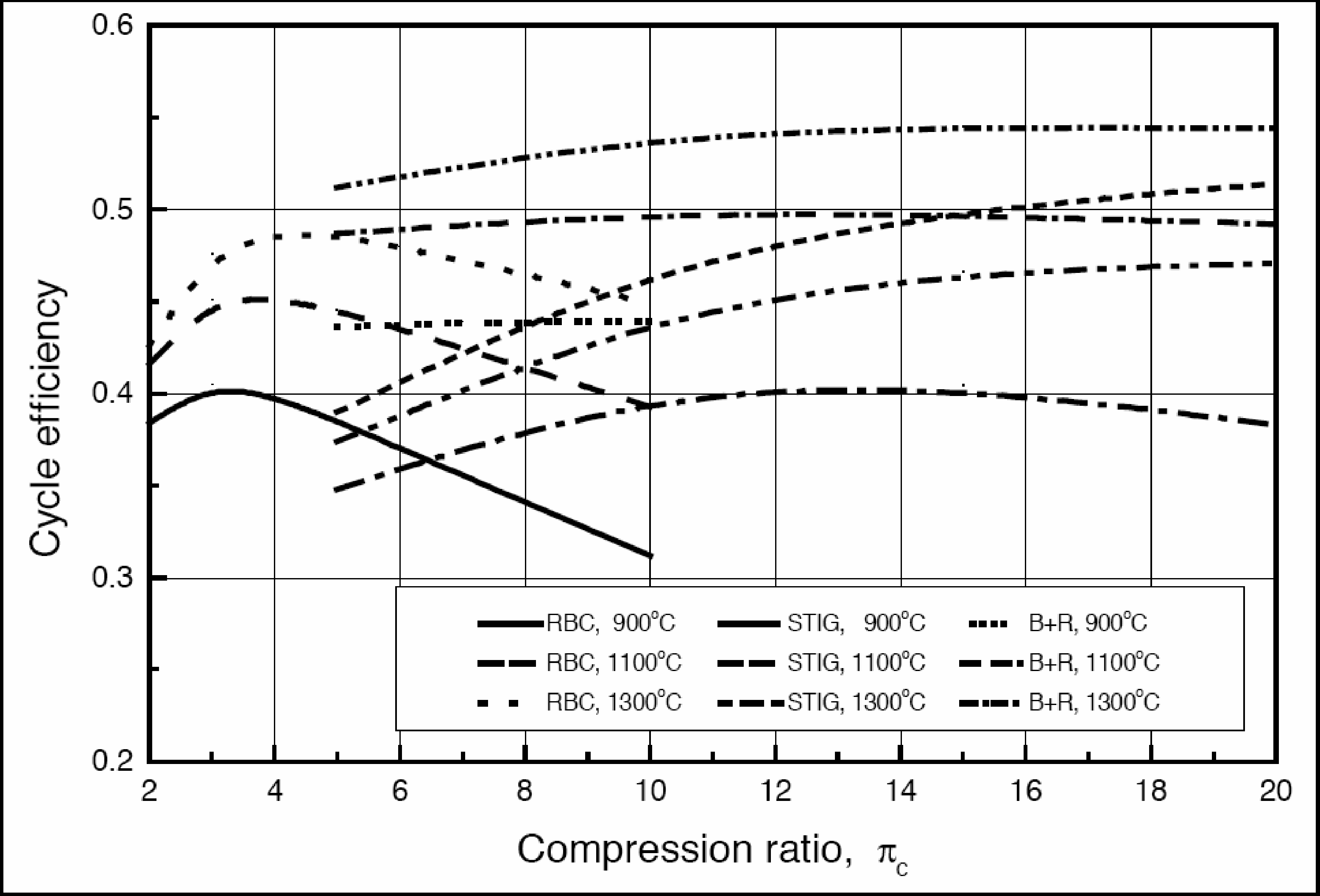


Brayton Cycle with steam Injection (STIG)

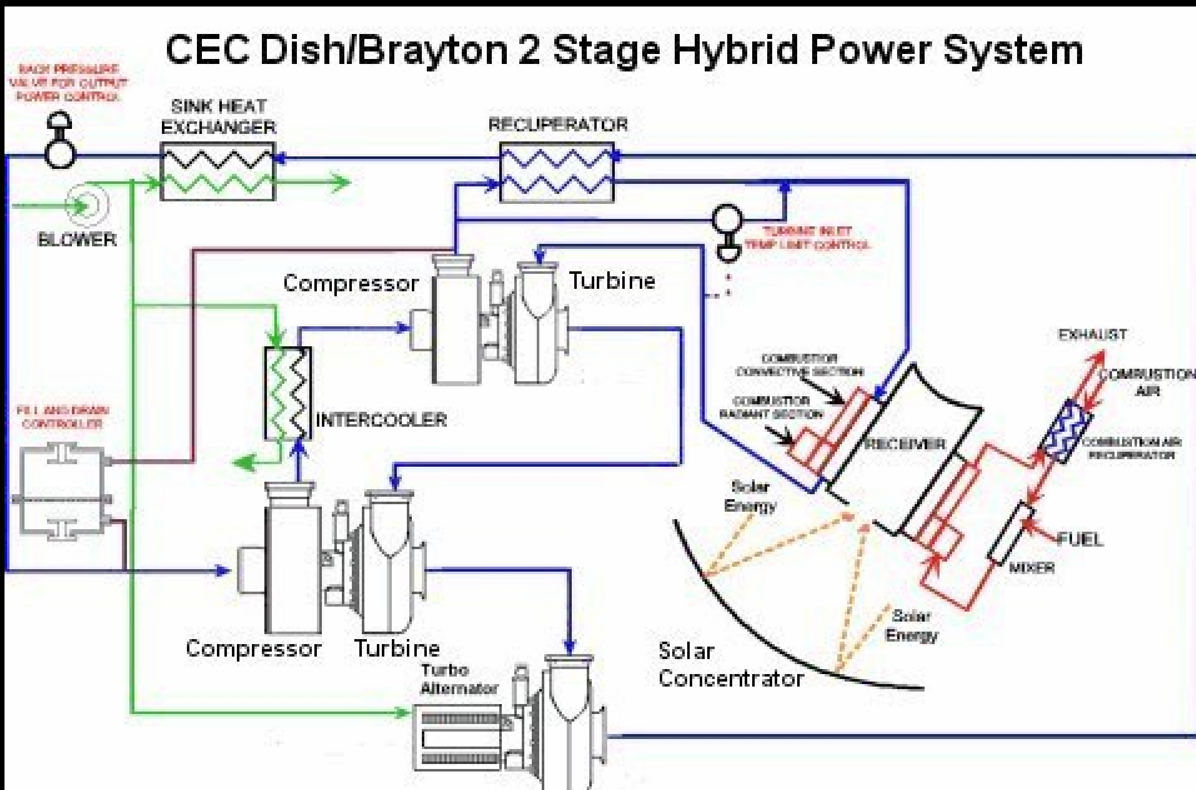


Combined Brayton -Rankine Cycle (B+R)

Cycle Efficiencies



Closed Solar Brayton Power Cycle

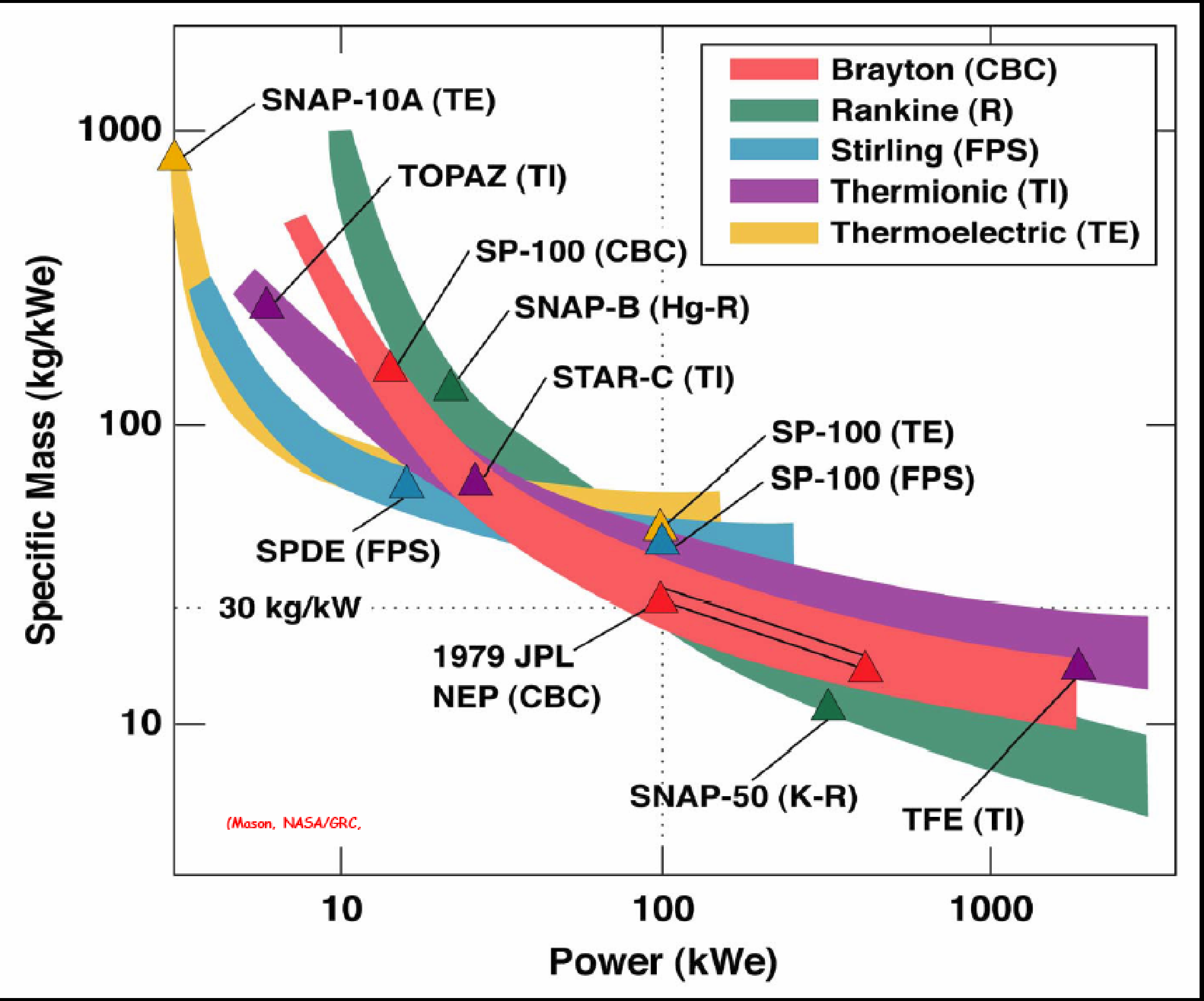


This concentric combustor surrounds the annular air passage of the working fluid (air) in its closed Brayton cycle. At full solar strength, without combustion augmentation, this two-stage turbo generator can produce an electrical output of up to 40 kW (equal to a 39% engine thermal efficiency).

The systems output can be augmented by the auxiliary gas combustor to produce up to 60 kW of electrical power. Utilization of the auxiliary combustor and closed Brayton cycle design make it possible for the turbo generator to operate efficiently over a full range of power conditions regardless of solar incidence.

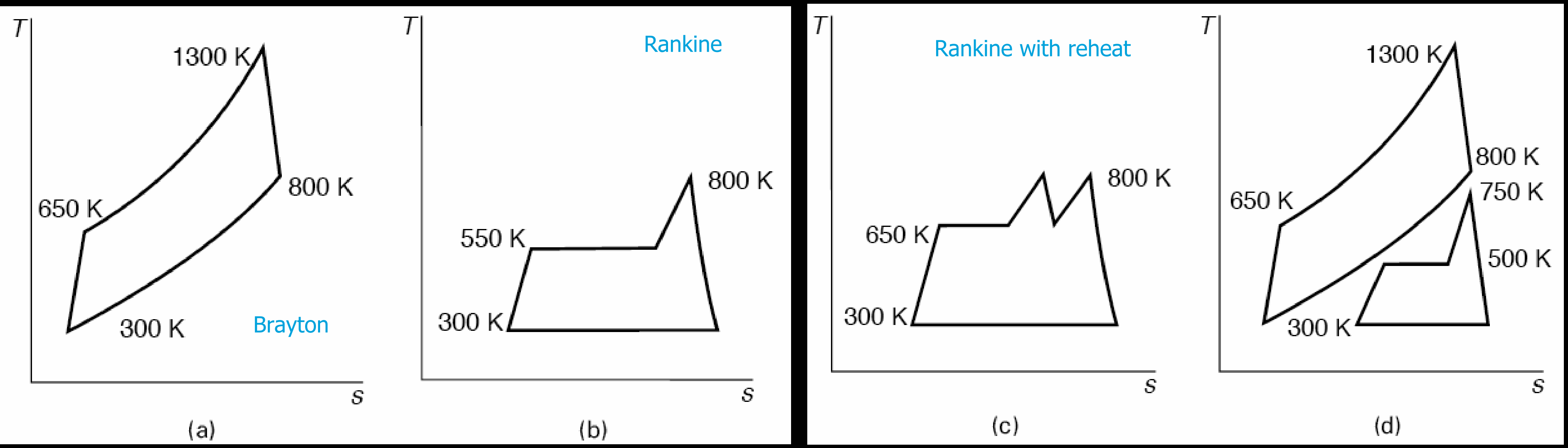
1999 Arthur D. Little Study for DOE

Thermodynamic Cycles



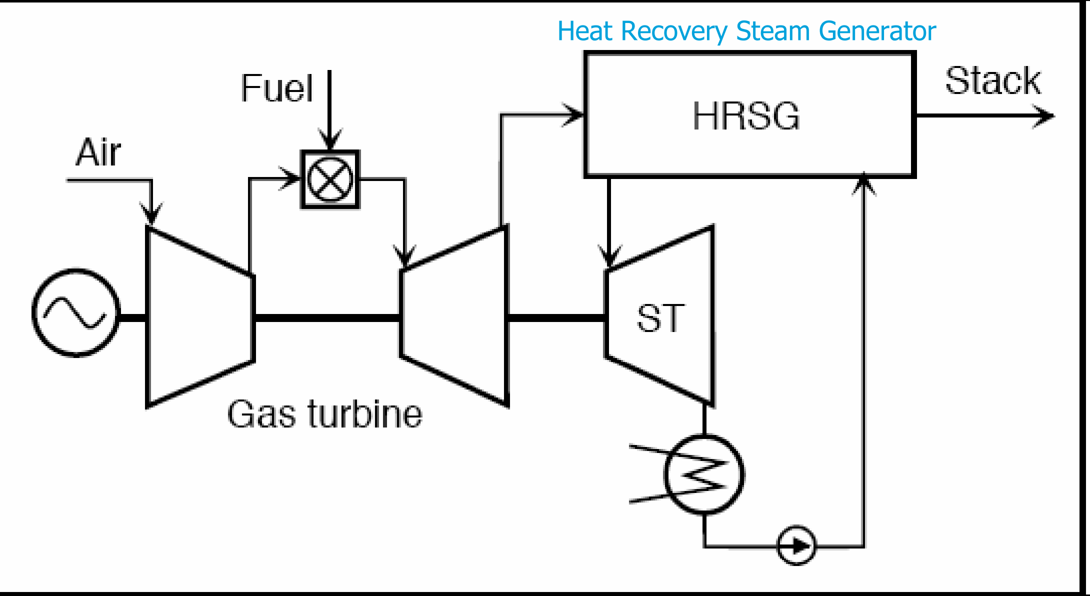
Mason, L.S., "Power Technology Options for Nuclear Electric Propulsion," Proceedings of the 37th Intersociety Energy Conversion Engineering Conference, IECEC–2002, Paper #20159, July 29–31, 2002.

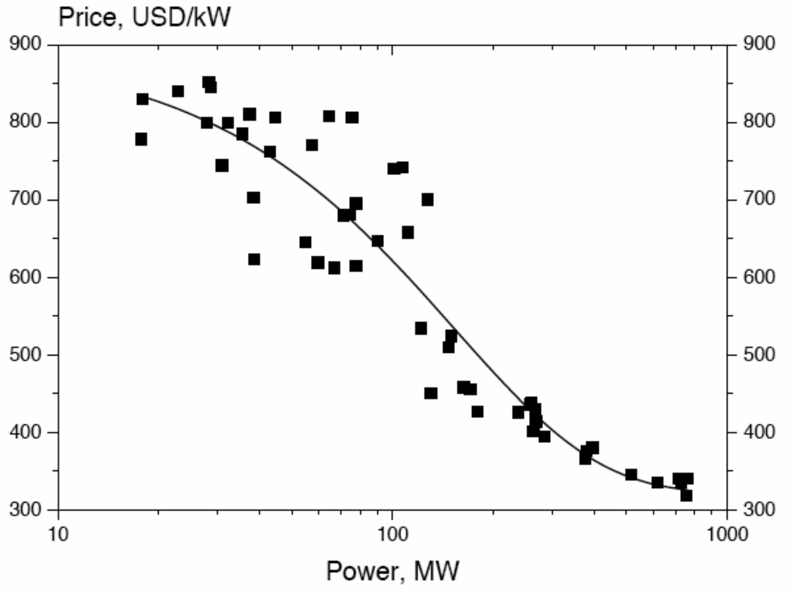
Combined Cycles



Plant	(a)	(b)	(c)	(d)
Average temperature of heat supplied, K	1000	600	680	1000
Average temperature of heat rejected, K	520	300	300	300
Carnot efficiency, %	48	50	56	70

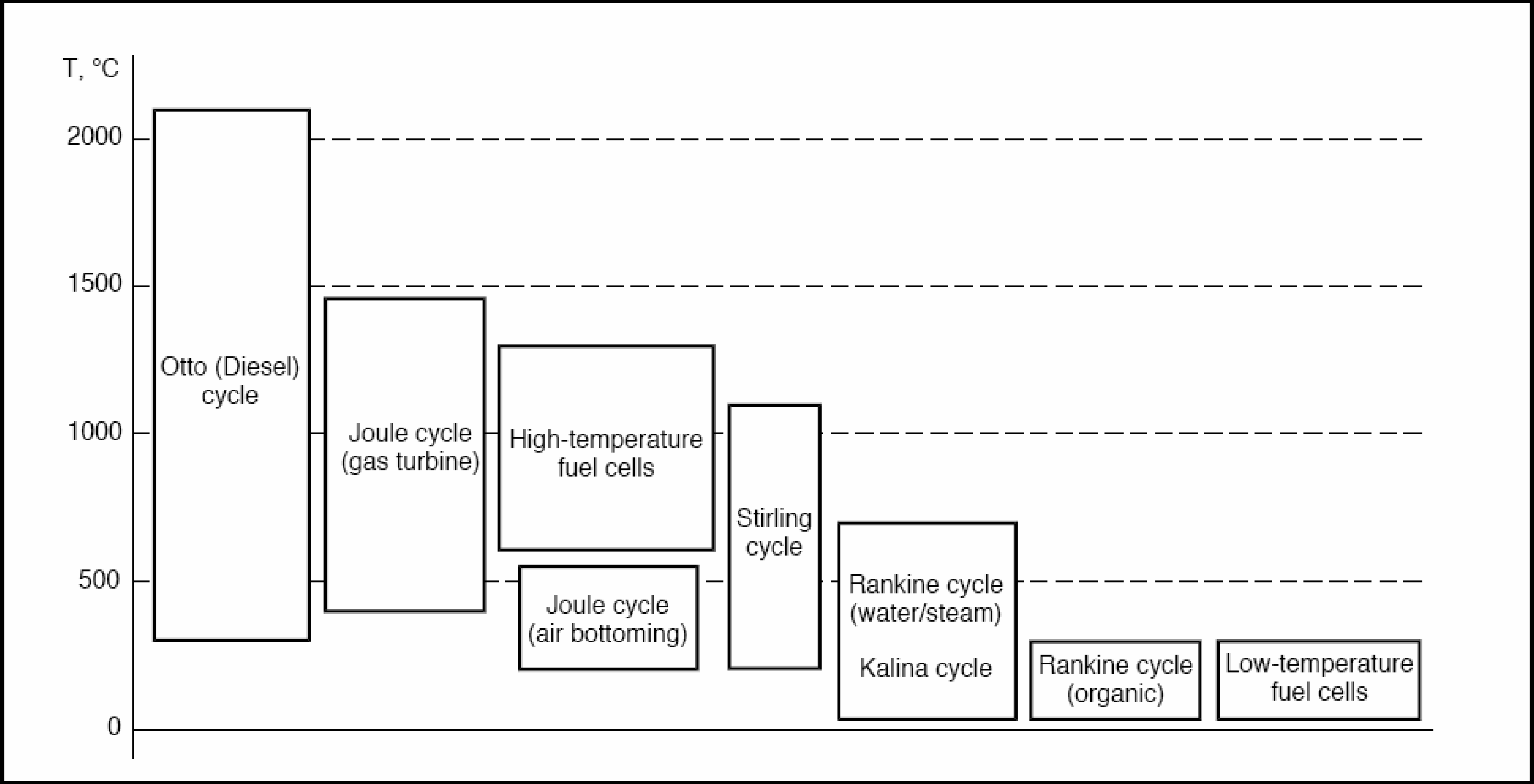
Combined Cycles





Power range, MW	Efficiency, %	HRSG type	Price, USD/kW
15–50	40–50	double pressure	650–850
51–100	44–52	double pressure	600–800
101–250	50–52	double- and triple-pressure	400–750
above 250	56–58	triple-pressure with reheat	350–450

Thermodynamic Cycles and Temperature Ranges



Source: M.A. Korobitsyn, "New and advanced energy conversion technologies. Analysis of cogeneration, combined and integrated cycles", ISBN 90 365 11070

A TRaNsient SYstems Simulation program (TRNSYS)