Supplementary Notes for

Chapter 14 Energy and Power Production,

Conversion, and Efficiency

1. Fundamental principles
   - energy conservation and the 1st Law of thermodynamics
   - entropy production and the 2nd Law of thermodynamics
   - reversible Carnot heat engines
   - maximum work / availability / exergy concepts

2. Efficiencies
   - mechanical device efficiency for turbines and pumps
   - heat exchange efficiency
   - Carnot efficiency
   - cycle efficiency
   - fuel efficiency
   - utilization efficiency

3. Ideal cycles
   - Carnot with fixed T_H and T_C
   - Carnot with variable T_H and fixed T_C
   - Ideal Brayton with variable T_H and T_C

4. Practical power cycles
   - an approach to Carnotizing cycles
   - Rankine cycles with condensing steam or organic working fluids
     - sub and supercritical operation
     - feed water heating
     - with reheat
   - Brayton non-condensing gas turbine cycles
   - Combined gas turbine and steam Rankine cycles
   - Topping and bottoming and dual cycles
   - Otto and diesel cycles for internal combustion engines

5. Examples of power conversion using a natural gas or methane energy source
   - sub-critical Rankine cycle
   - gas turbine open Brayton cycle
   - combined gas turbine steam Rankine cycle
   - electrochemical fuel cell

For further information, refer to:

1. Milora, S.L. and Tester, J.W. *Geothermal Energy as a Source of Electric Power*. Cambridge, MA: MIT Press, 1976, especially chapters 3-5.

2. Balje, O.E. *Turbomachines*. New York: John Wiley and Sons, 1981.

3. Balje, O.E. *Journal of Engineering for Power*, ASME Transactions **84**(1), 83, January 1962.

Power Cycles

1. Rankine Cycle Limitations

- utilization vs. cycle efficiency (η_u vs. η_c)

- "Carnotizing" to approach 2nd law limit of performance

- mechanical component efficiencies η_t , η_p < 1 for turbines and feed pumps (effect of moisture to decrease efficiency)

- heat transfer irreversibilities ($\Delta T > 0$ in primary heat exchanger and condenser)

- materials limitations (metallurgical limit for steel in steam Rankine cycle 600°C (1100°F)

2. Improvement to Rankine Cycle (fossil or nuclear-fired)

- reheat

- supercritical vs. subcritical operation with steam

- decrease turbine exhaust pressure/condensing temperature

- regenerative feed water heating/interstage moisture extraction
- topping and bottoming cycles using non-aqueous fluids (topping - Hg, Cs, K; bottoming - NH_3, halocarbons)
- combined cycles (gas turbine cycle linked to steam cycle)

3. *Power Generation with Low Temperature Heat Sources (solar, geothermal, etc.)*

- cycle configurations possible
- analysis of single and multi-single flash systems
- single (binary), sub- and supercritical cycles using non-aqueous working fluids
- derived thermodynamic property estimation from EOS, ρ_{liquid}, P_{vp}^{sat}, and C_p^* correlations
- effect cycle pressure on performance with an R-115 and a 150°C resource
- irreversibility analysis of performance as function of turbine inlet pressure
- η_u vs. temperature for several fluids
- correlation of "degree of superheat" for optimal performance vs. C_p^*/R

4. *Thermodynamic Analysis of Fluid Flow in a Duct or Nozzle*

- thermodynamic analysis of fluid flow in a duct or nozzle
- conversion of *KE* into rotating shaft work
- sonic limitations in choked flow (pressure ratio, isentropic ΔH)

5. *Turbine, Pump and Compressor Sizing and Performance*

- Balje analysis of performance ($\eta = f[N_s, D_s, Re, Ma]$)
- generalized approach to turbine exhaust and requirements
- sizing figure of merit

Power Cycle Terminology

$$\eta_c = \text{cycle efficiency} = \frac{\text{net work}}{\text{primary heat exchanged}} = \frac{W_{net}}{Q_H}$$

$$\eta_u = \frac{\text{net work}}{\text{maximum possible work}} = \frac{W_{net}}{W_{\max}} = \frac{W_{net}}{\Delta B}$$

ΔB = availability change = $\Delta H - T_o \Delta S = W_{max}$

T_o = ultimate sink temperature for heat rejection

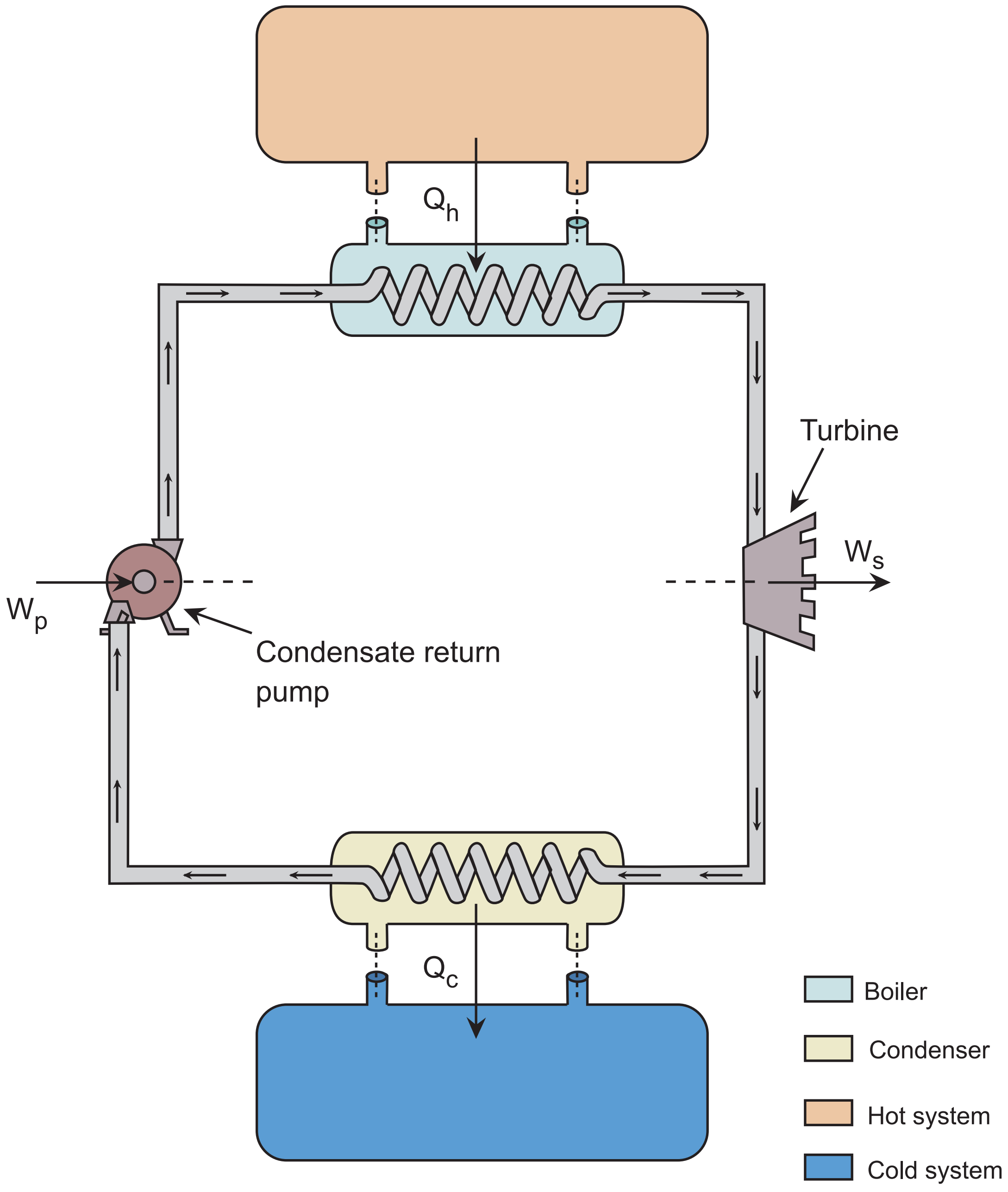
P_o = ambient pressure

For example, for geothermal systems, at steady state

$$\Delta B \equiv \Delta H - T_o \Delta S \Bigg|_{T_o, P_o}^{T_{gf}, P_{gf}}$$

where T_{gf} = geothermal fluid inlet temperature
P_{gf} = geothermal fluid inlet pressure

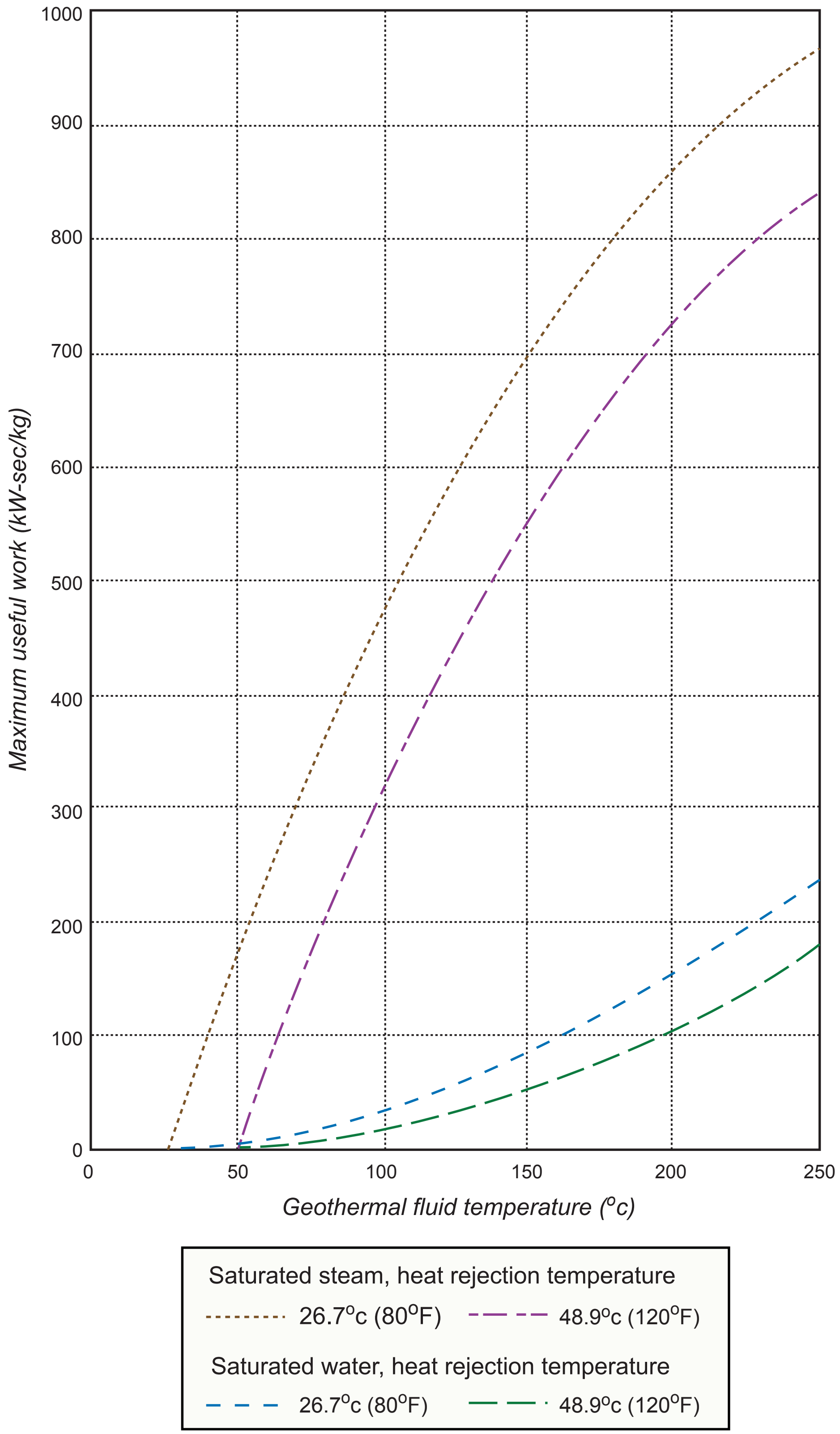
As the cost of producing the geothermal fluid (drilling wells, etc.) increases relative to the cost of the power conversion equipment itself (heat exchangers, turbines, pumps, etc.), cycle operation at conditions approaching max η_u is favored. See Chapters 3 and 4 of Milora and Tester (1976) for further discussion.



General Rankine Cycle Schematic

Adapted from Tester, J. W. and Modell, Michael. *Thermodynamics and Its Applications*. Upper Saddle River, NJ: Prentice Hall PTR, 1997, p. 606, Figure 14.7.

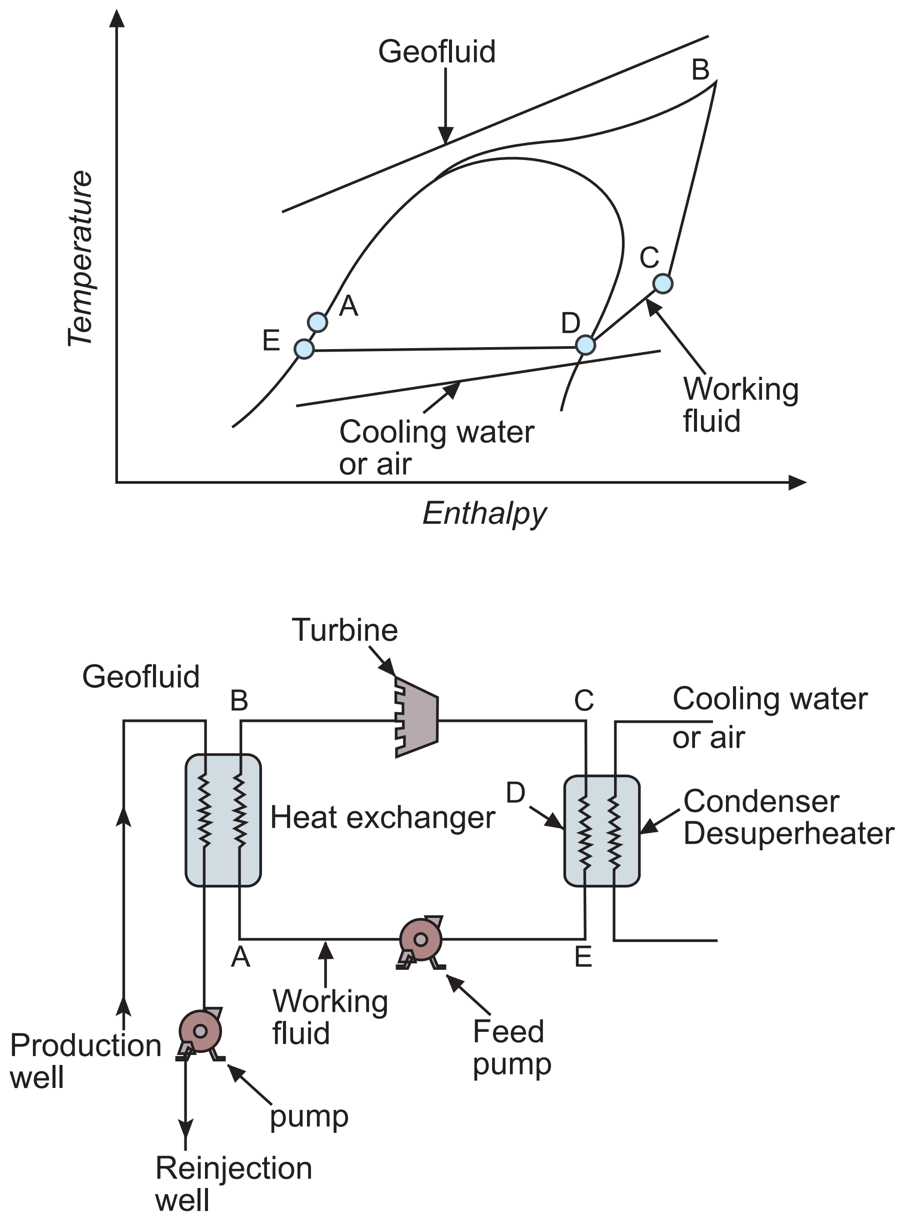
Image by MIT OCW.



Availability or maximum useful work as a function of geothermal fluid temperature.

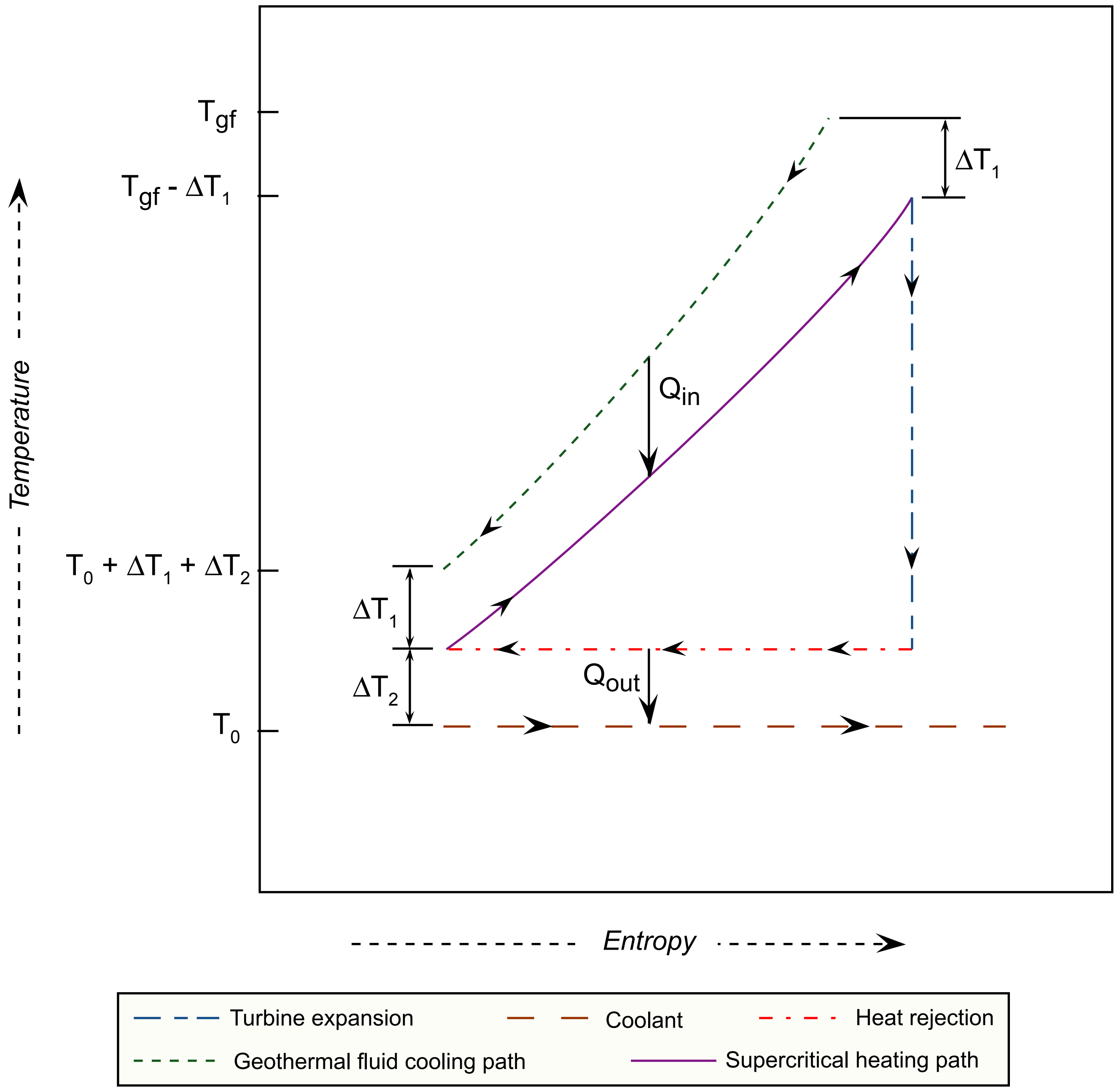
Image by MIT OCW.

Supercritical Rankine Cycle



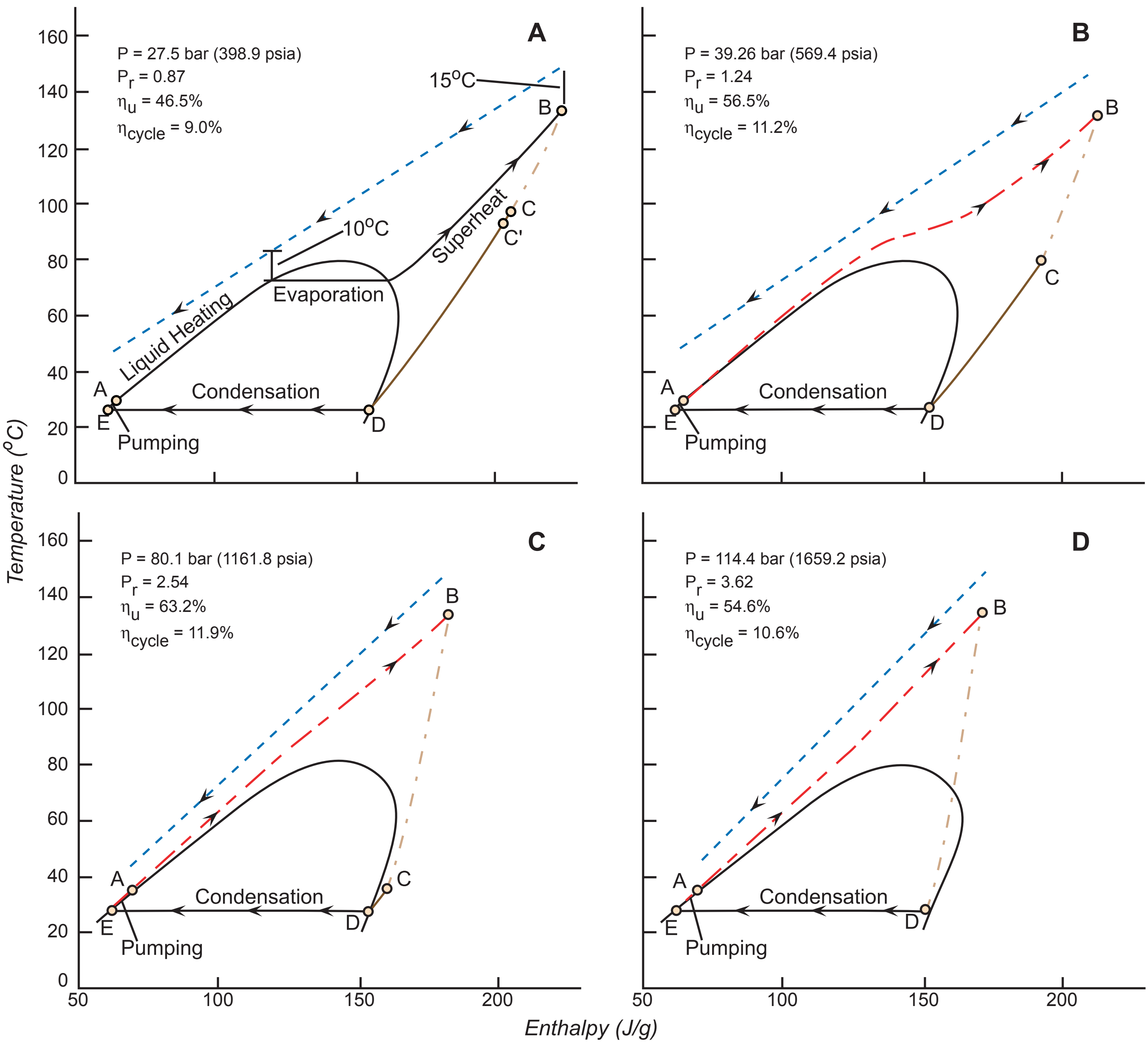
Supercritical Rankine cycle operating state points on a temperature-enthalpy (T-H) diagram.

Image by MIT OCW.



Temperature-entropy (T-S) plot for an idealized or "Carnotized" power cycle. Note that as ΔT_1 and ΔT_2 go to zero that maximum work output is achieved.

Image by MIT OCW.



C_2F_5Cl
MW = 154.5 g/mol
P_C = 458 psia (32 bar)
T_C = 80°C psia (175.9°F)

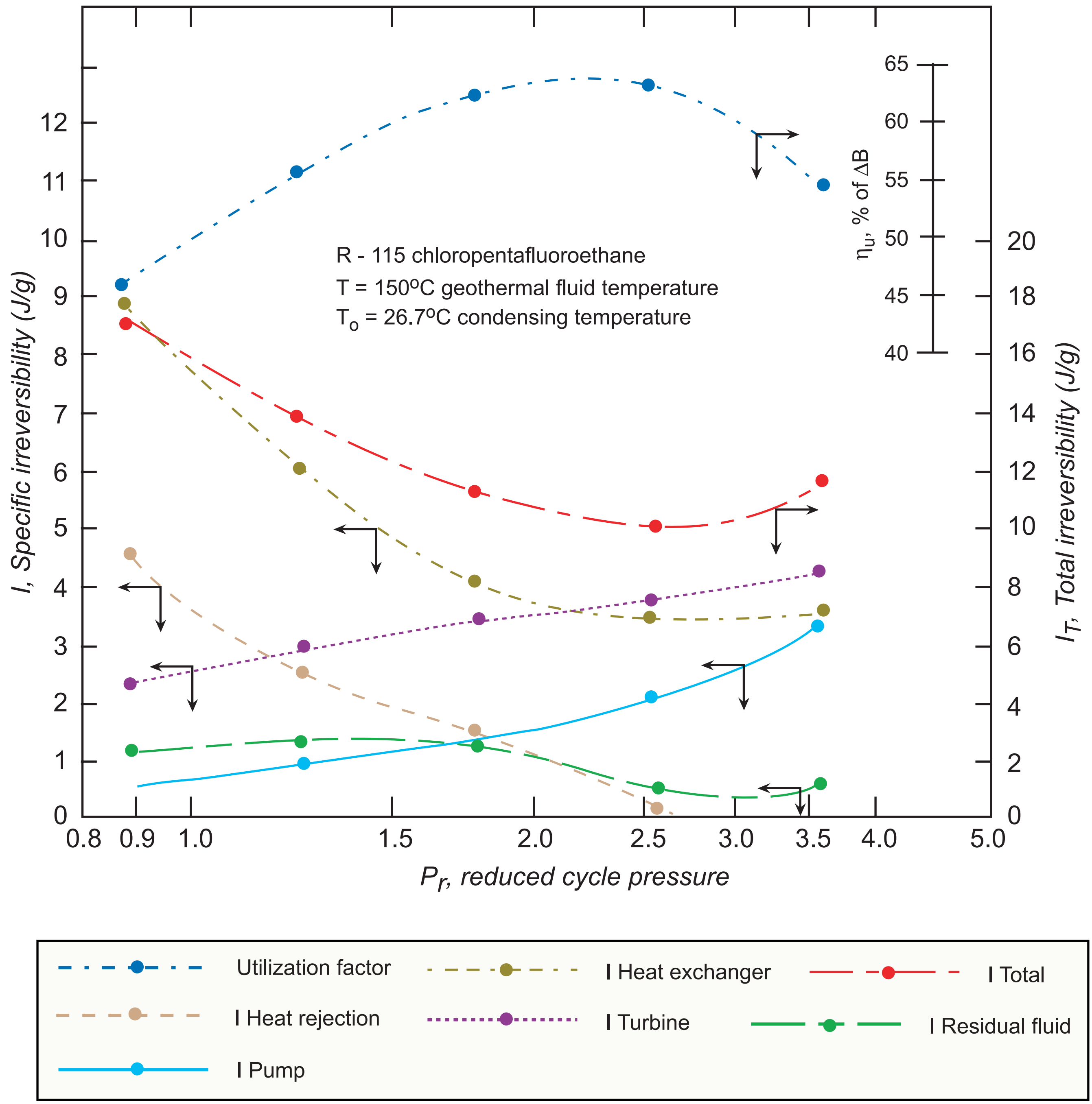
R-115 Chloropentafluoroethane
T_{gf} = 15.0° C
T_o = 26.7° C

η_t = 85% dry
η_p = 80%

Geothermal Fluid Cooling Path	Supercritical Heating Path
Turbine Expansion	Sensible Heat Rejection

Approach to thermodynamically optimized Rankine cycle for R-115 with a 150°C liquid geothermal fluid source and heat rejection at 26.7°C (80°F). Temperature-enthalpy (T-H) diagrams shown at different reduced cycle pressures.

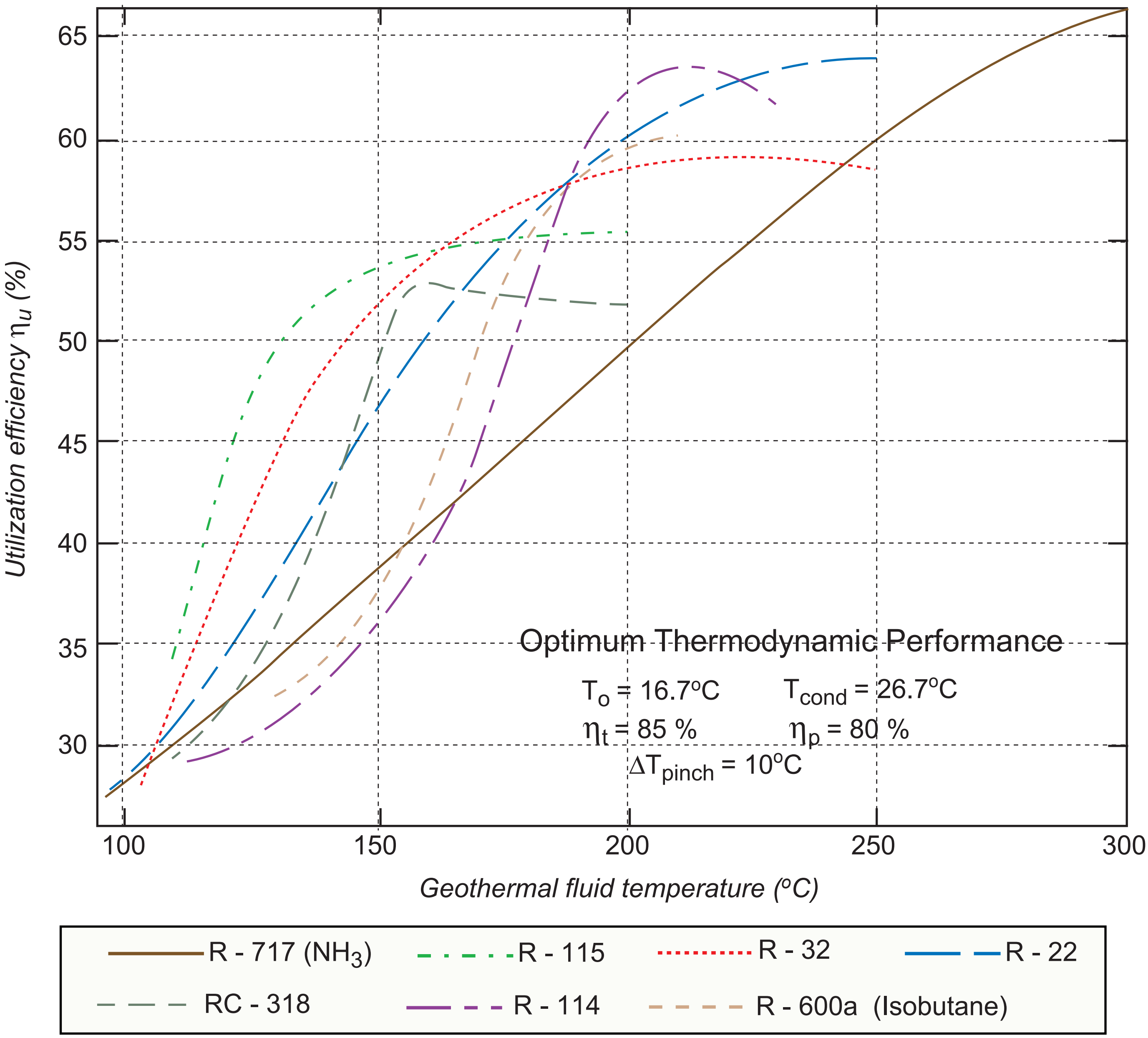
Adapted from Tester, J. W. and Modell, Michael. *Thermodynamics and Its Applications*. Upper Saddle River, NJ: Prentice Hall PTR, 1997, p. 49, Fig. 14.10.



Component irreversibility and η_u as a function of reduced cycle pressure for R-115 for the condition shown in the figure above.

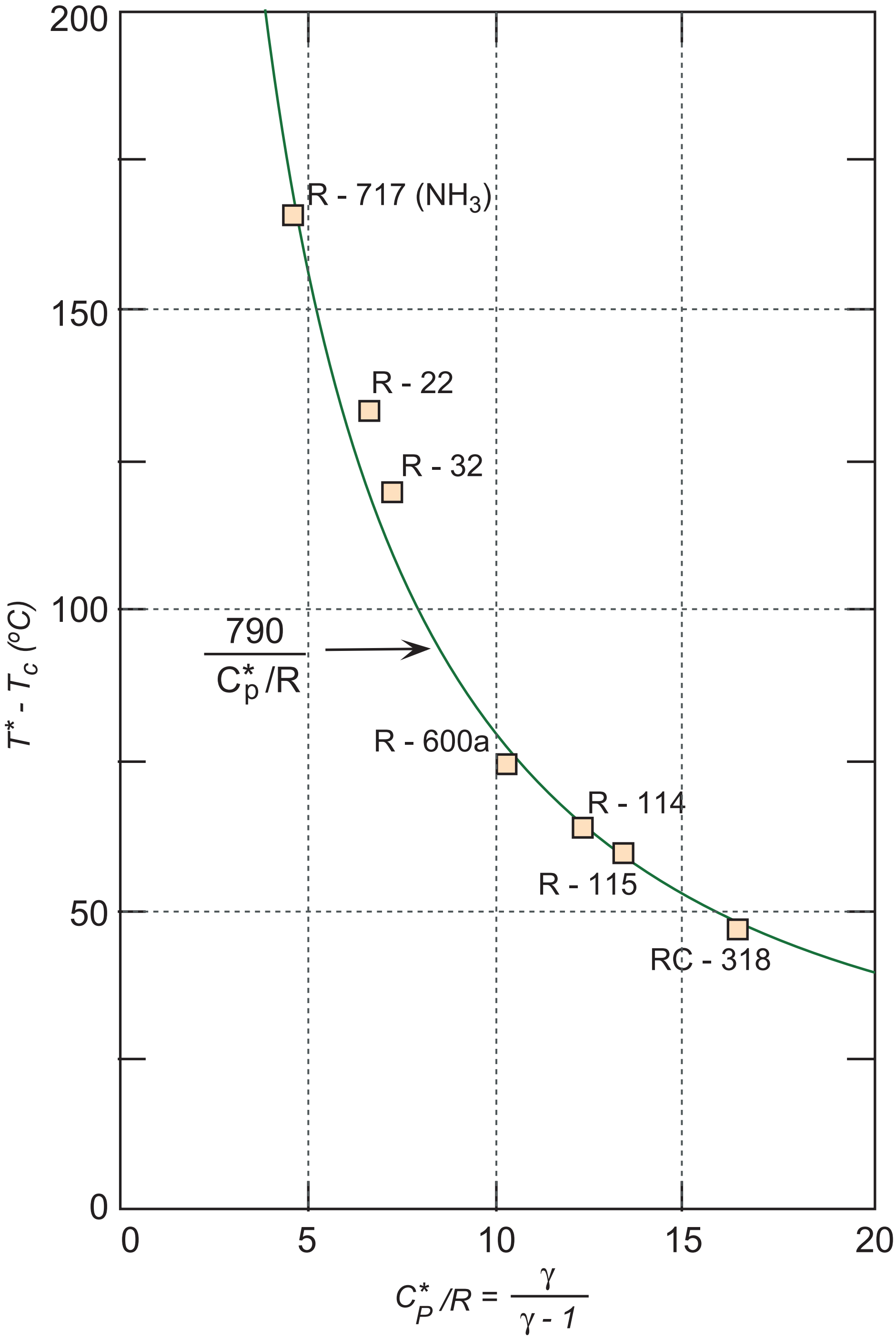
Adapted from Tester, J. W. and Modell, Michael. *Thermodynamics and Its Applications*. Upper Saddle River, NJ: Prentice Hall PTR, 1997, p. 613, Fig. 14.11.

Image by MIT OCW.



Utilization efficiency η_u as a function of geothermal fluid (initial heat source) temperature for optimum thermodynamic operating conditions.

Image by MIT OCW.



Generalized correlation for the degree of superheat above the critical temperature for optimum utilization of geothermal fluid availability as a function of ideal gas state reduced heat capacity.

Image by MIT OCW.