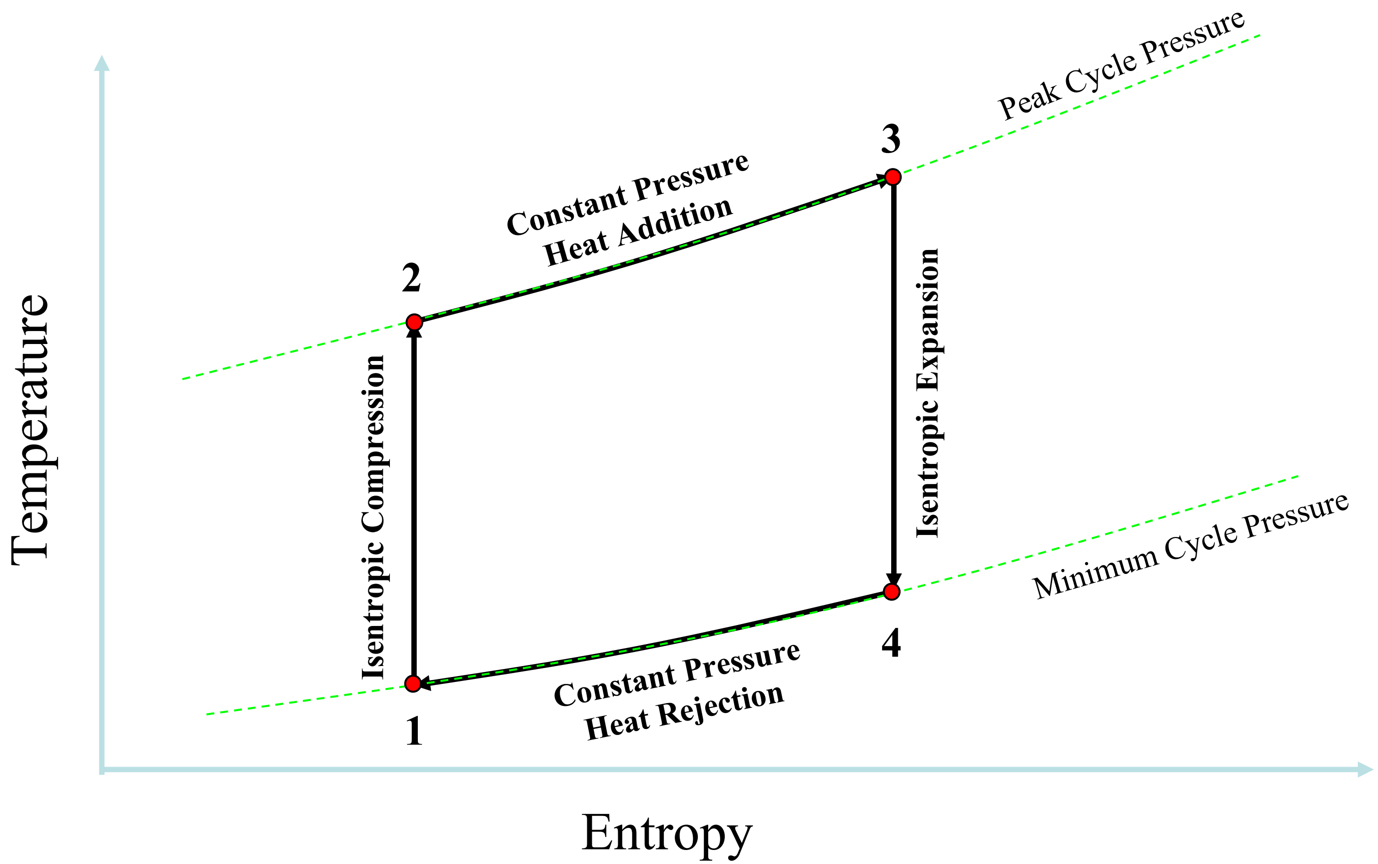
Thermodynamics Overview

Contents

- Brayton Cycle Basics
- Flow Parameter
- Cycle Deck
- Firing Temperature
- Control Curve

Ideal Brayton Cycle

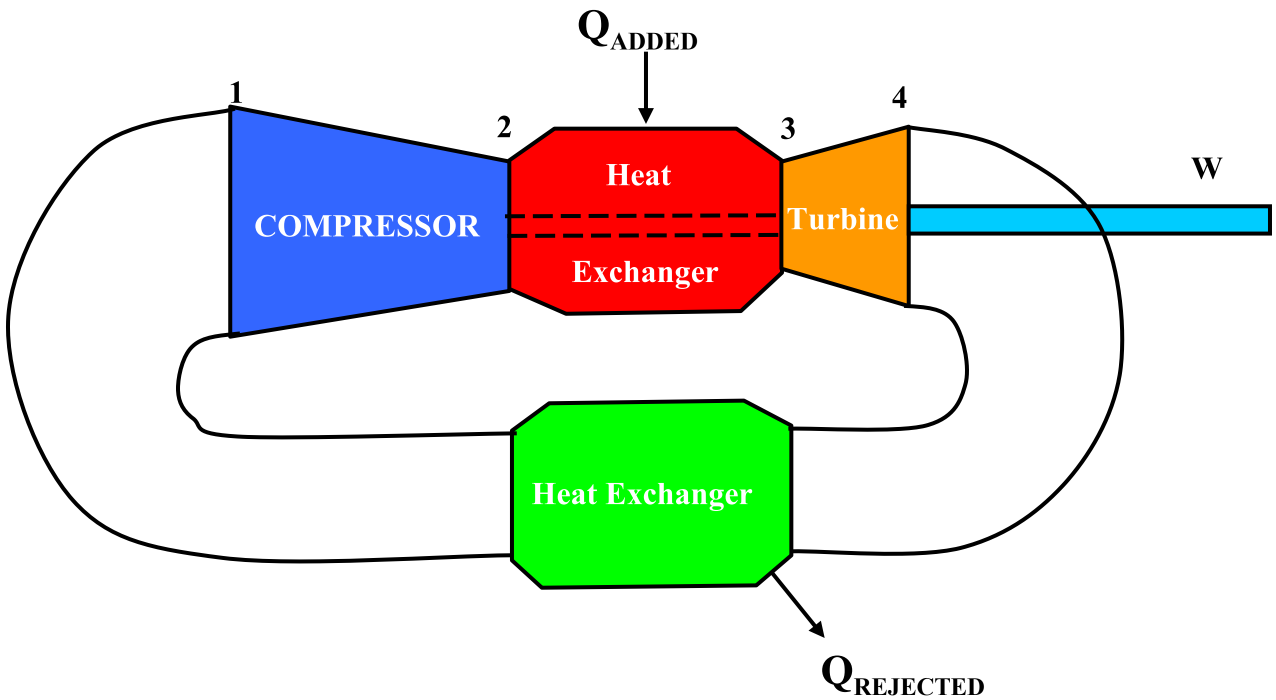
Four Thermodynamic Processes



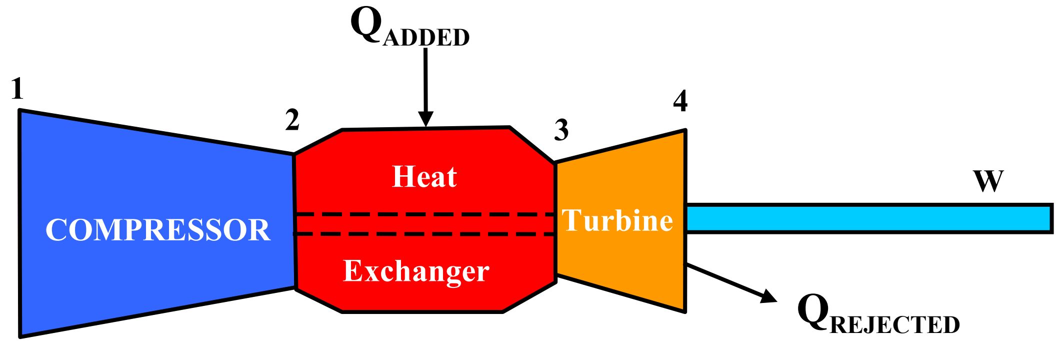
Brayton Cycle

Gas Turbine Application

CLOSED
CYCLE



OPEN
CYCLE



Ideal Brayton Cycle

Cycle Efficiency

Definition:

$$\eta_{\text{Cycle}} = \frac{\text{Work Output}}{\text{Heat Added}} = \frac{(T_3 - T_4) - (T_2 - T_1)}{(T_3 - T_2)}$$

Re-Arranging and Substitution Using:

$$\eta_{\text{Cycle}} = 1 - \frac{1}{\left(\dfrac{P_2}{P_1}\right)^{\gamma - 1/\gamma}} \qquad \frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\gamma/\gamma - 1} = \frac{P_3}{P_4} = \left(\frac{T_3}{T_4}\right)^{\gamma/\gamma - 1}$$

Yields Cycle Efficiency = f (P_2/P_1):

$$\eta_{\text{Cycle}} = 1 - \frac{1}{\left(\dfrac{P_2}{P_1}\right)^{\gamma - 1/\gamma}}$$

Brayton Cycle

Other Considerations

- Maximum Allowable Cycle Temperature
  - Material Limitations
  - Cooling Technologies
- Optimum Work Output
  - Selection of Design Pressure Ratio
- Non-Ideal Cycle Effects
  - Compression/Expansion Inefficiencies
  - Pressure Losses
  - Parasitic Flows

Ideal Brayton Cycle

Optimum Work – Selection of Pressure Ratio

Work Output:

$$W = C_P\left[\left(T_3 - T_4\right) - \left(T_2 - T_1\right)\right]$$

Isentropic Relationships yield:

$$T_4 = T_3\left[\frac{T_1}{T_2}\right] \quad \textit{when} \quad \frac{P_3}{P_4} = \frac{P_2}{P_1}$$

Differentiate with respect to T2:

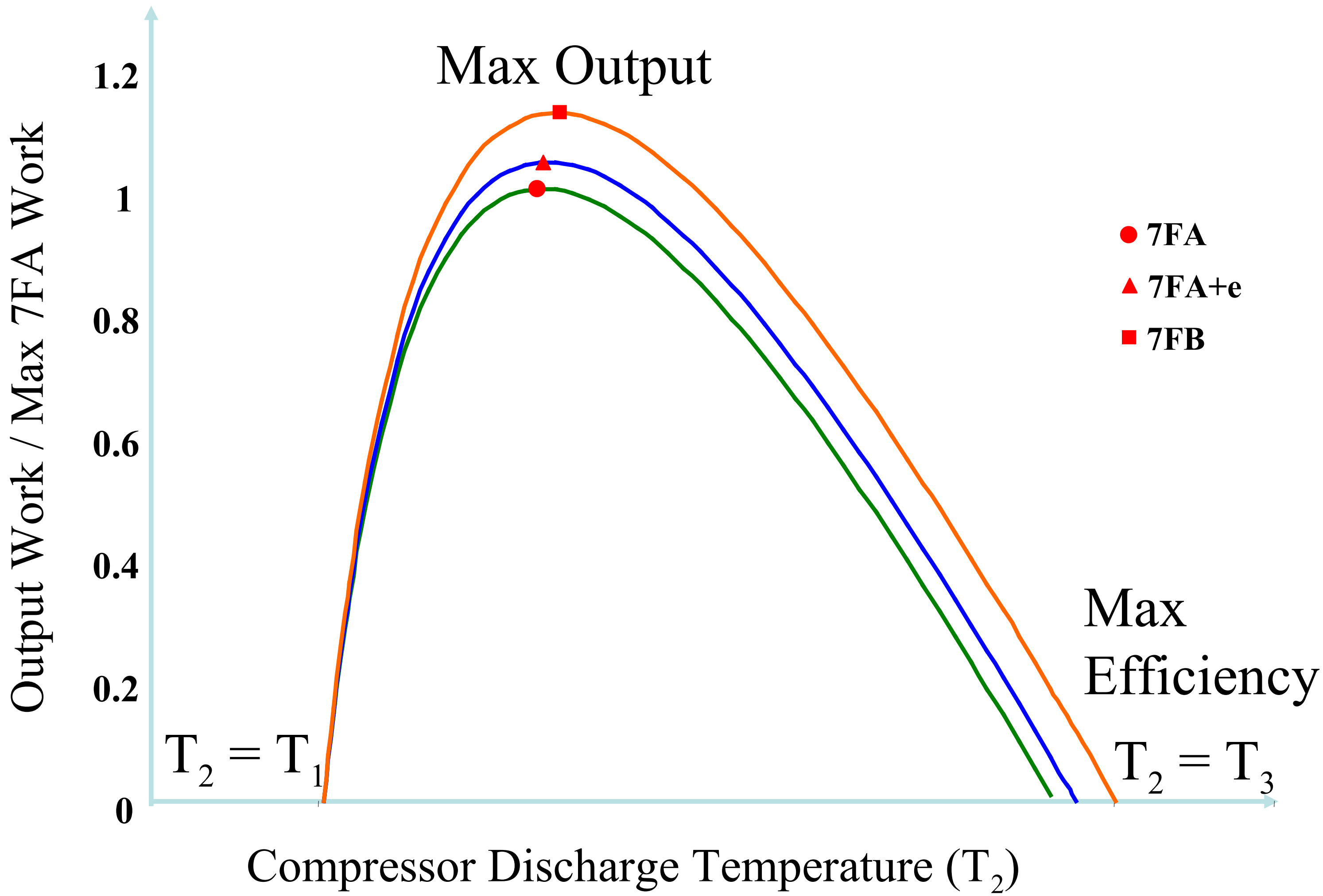
$$\frac{dW}{dT_2} = C_P\left[0 + \frac{T_3 T_1}{T_2{}^2} - 1 + 0\right]$$

Set to Zero and Solve for T2:

$$T_2 = \sqrt{T_3 T_1}$$

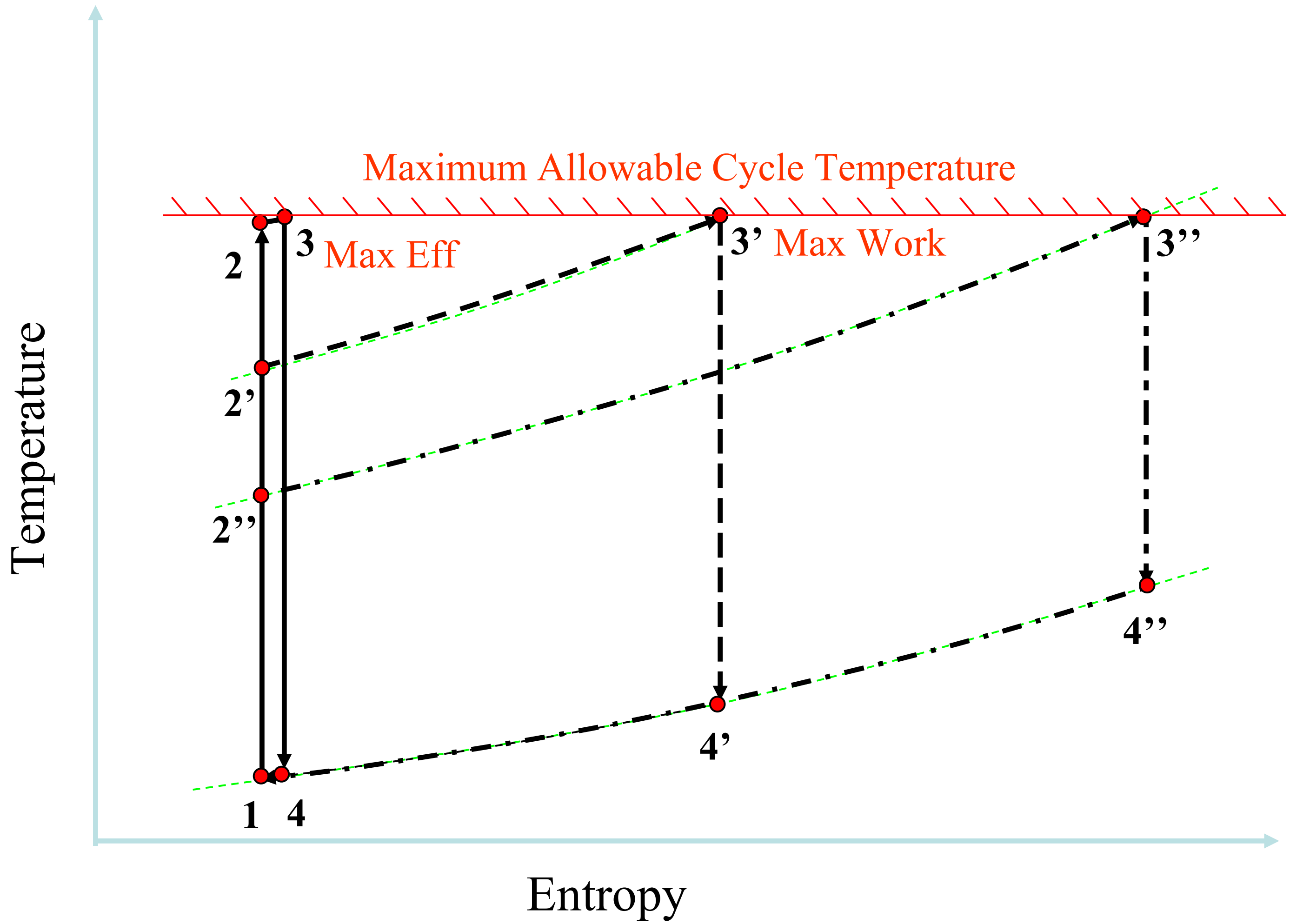
Ideal Brayton Cycle

Normalized Output Work vs. T_2 with Lines of Constant T_1 and T_3



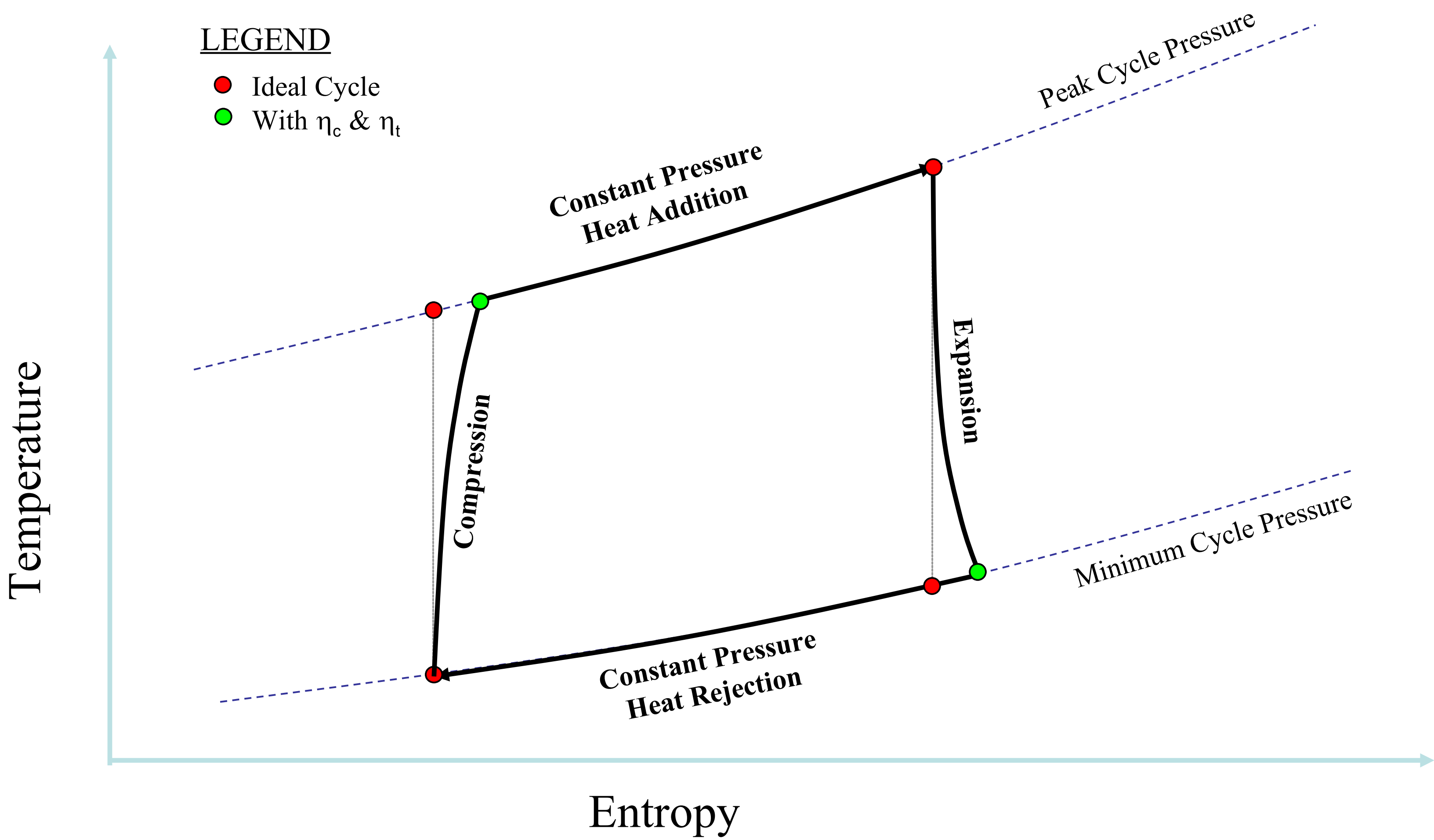
Ideal Brayton Cycle

Maximum Work vs. Maximum Efficiency



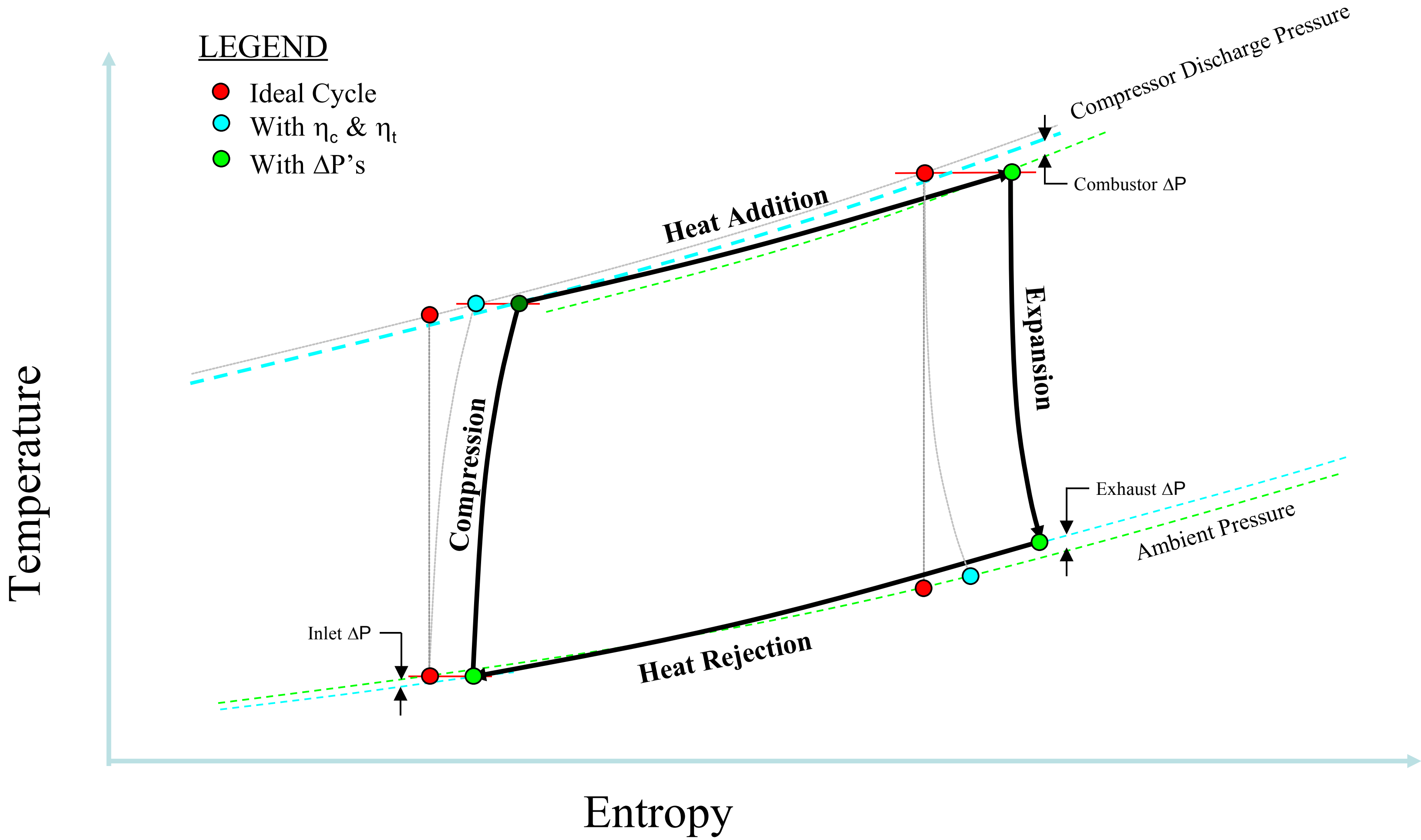
Brayton Cycle

Compression and Expansion Inefficiencies



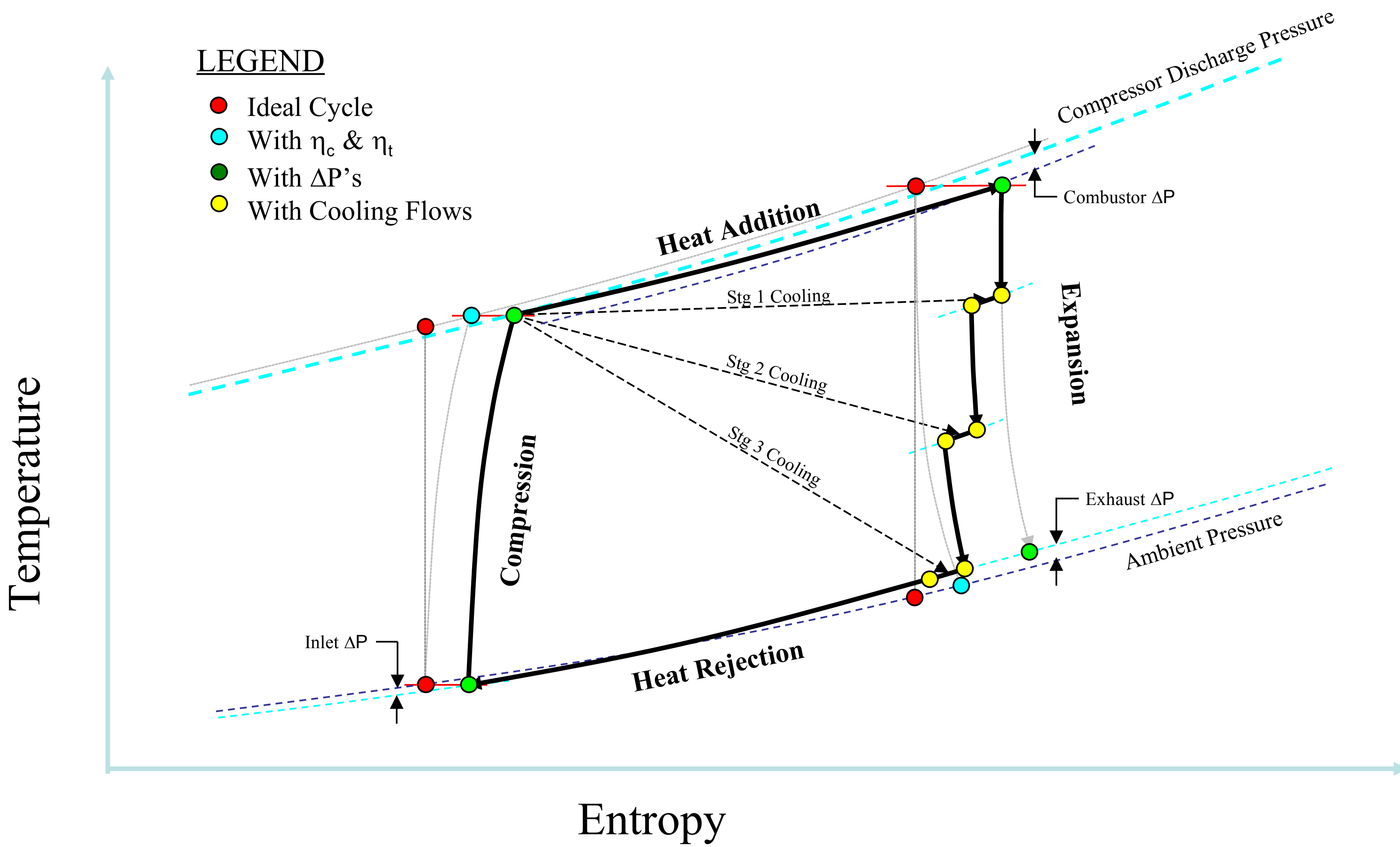
Brayton Cycle

Pressure Losses - Inlet, Combustor, Exhaust



Brayton Cycle

Parasitic Flows for Turbine Cooling



Flow Parameter - Defined

Starting from basic continuity equation:

$$W = \rho \times A \times V$$

Through substitution of thermo & compressible flow principles, then re-arranging terms:

$$\frac{W\sqrt{T_0}}{P_0 A} = \sqrt{\frac{\gamma}{R}}M \frac{\sqrt{1+\frac{\gamma-1}{2}M^2}}{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}}$$

Flow Parameter - Applied

Setting M = 1 (Choked Flow at Station 3)

$$\frac{W\sqrt{T_3}}{P_3 A_3} = Const$$

Given:

Machine Size $\propto$ W

Technology $\rightarrow T_3$

Max Output $\rightarrow P_3$

A_3 is set to hold continuity

Brayton Cycle General Observations

- For Ideal Cycle
  - Cycle efficiency increases with P_2/P_1, and not dependent on T_3
  - For given P_2/P_1, as T_3 increases, all additional energy input becomes work output
- For Real Cycle
  - (T3 at Zero Work)Real > (T3 at Zero Work)Ideal
  - As T3 increases, both cycle efficiency & work output increase
  - Therefore, general conclusion is higher T3 is good

Gas Turbine Performance Estimator (Cycle Deck)

Customers can register and then download GTP Estimator by going to:

http://www.gepower.com/home/index.htm

GTP (Cycle Deck) - The Primary Gas Turbine Thermodynamic Tool

- An aero-thermal math model of the entire GT cycle (Thermodynamics, Aerodynamics, Compressible Flow, Heat Transfer)
- Built & maintained by Systems Engineering
- Uses:
  - Boundary conditions for component designers
  - Performance prediction (Guarantees, Correction Curves, Studies)
  - Control schedule development (T_x Control, IGV Control, etc.)
  - Data reduction/analysis
  - Core of performance monitoring programs

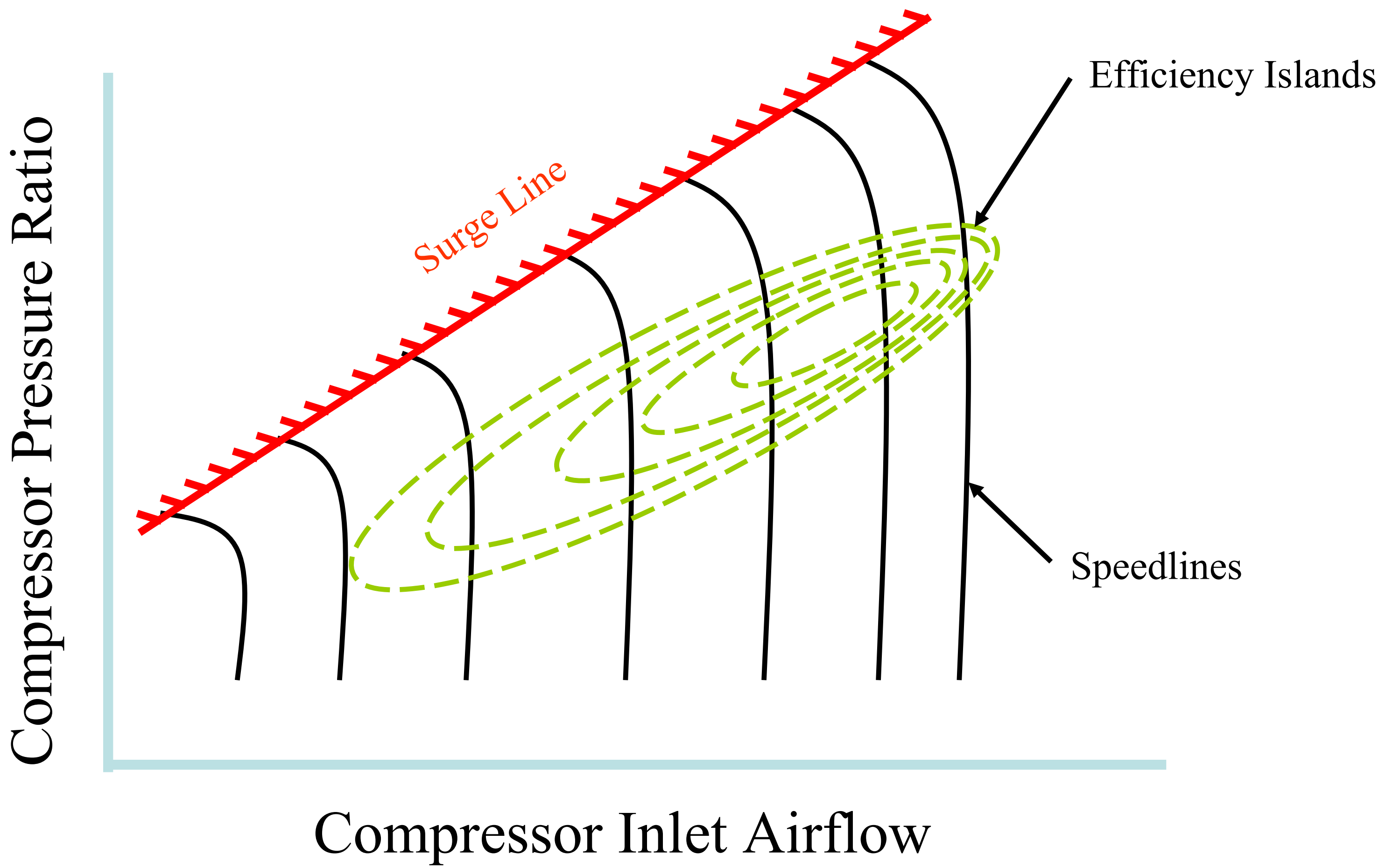
GTP (Cycle Deck) - Modular

Control System & Iteration & Convergence

Module	Inputs	Outputs
Inlet System	• Ambient Conditions • Inlet ΔP • IBH Functionality	• Compressor Inlet Conditions
Compressor	• Rotational Speed • Pressure Ratio • IGV Angle	• Inlet/Exit Flow Rate • Overall Efficiency • Compressor Exit & Extraction Point Conditions
Parasitic Flows	• Compressor Flow Conditions • Design Cooling Flow Fractions • Flow Parameter Characteristic	• Flow Rate Down Each Circuit
Combustor	• Compressor Exit Conditions • Fuel & Diluent Flow & Composition • Design Point ΔP/P	• ΔP/P • Combustor Exit Gas Conditions & Composition • Nox & CO
Turbine	• Combustor Exit Conditions • Dilution Air Proportions	• Stage by Stage Exit Conditions • Bucket Relative Temperatures
Exhaust System	• Turbine Exit Conditions • Design Point ΔP	• ΔP/P
Generator	• Shaft Power • Power Factor	• Generator Electrical Losses • Electrical Power Output
Cycle Performance	• Flows, Enthalpies Throughout Cycle	• Power Output, Heat Rate, Cycle Efficiency

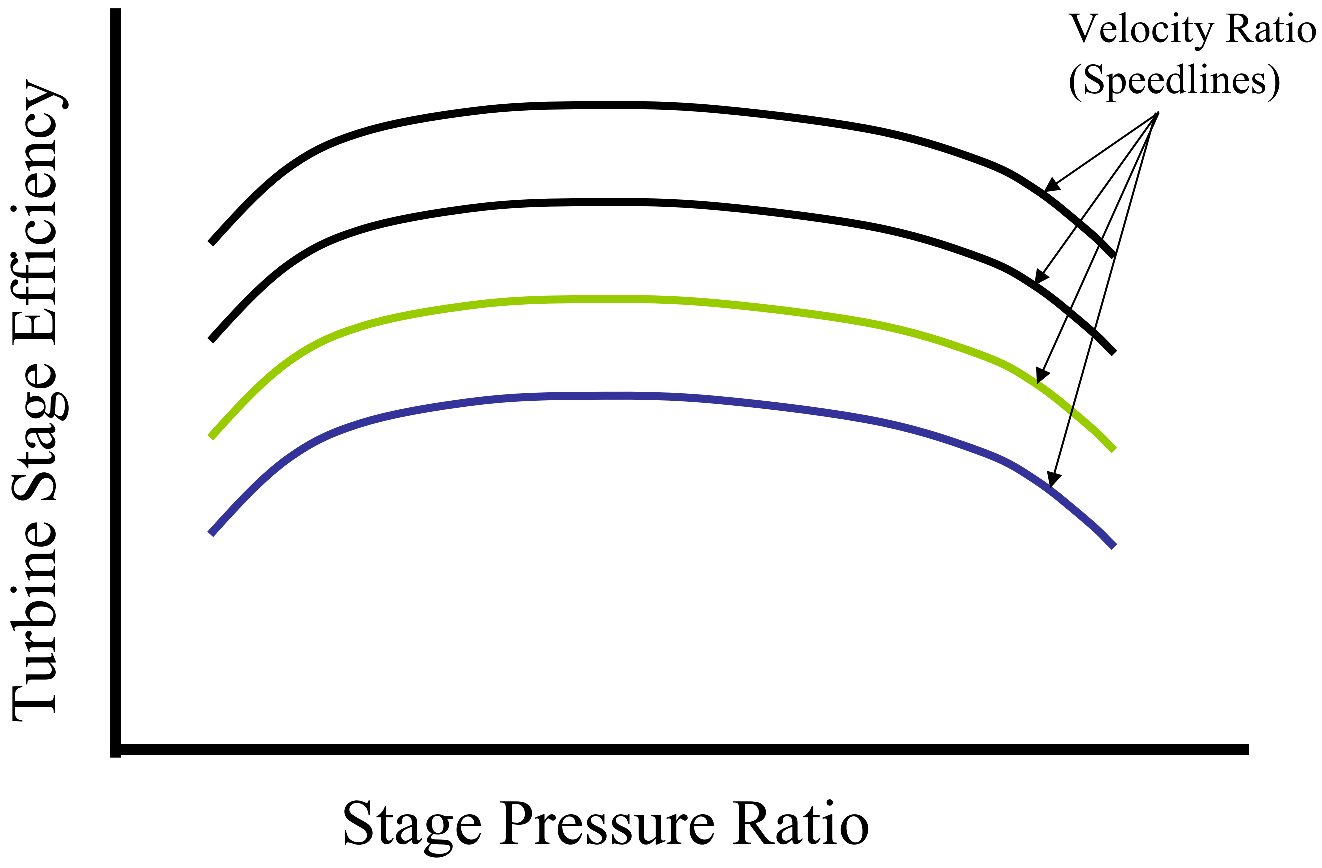
GTP (Cycle Deck)

Compressor Map



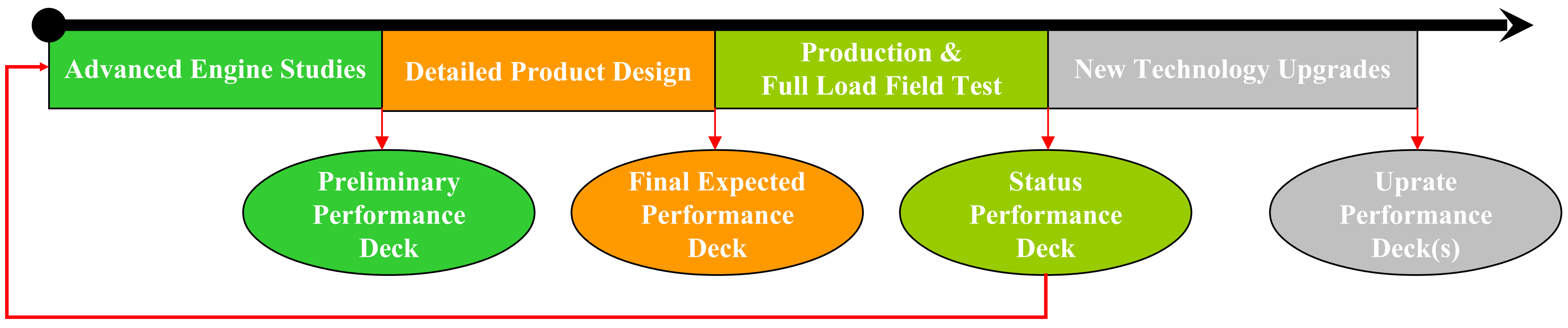
GTP (Cycle Deck)

Turbine Map



GTP (Cycle Deck)

Four Stage Life Cycle

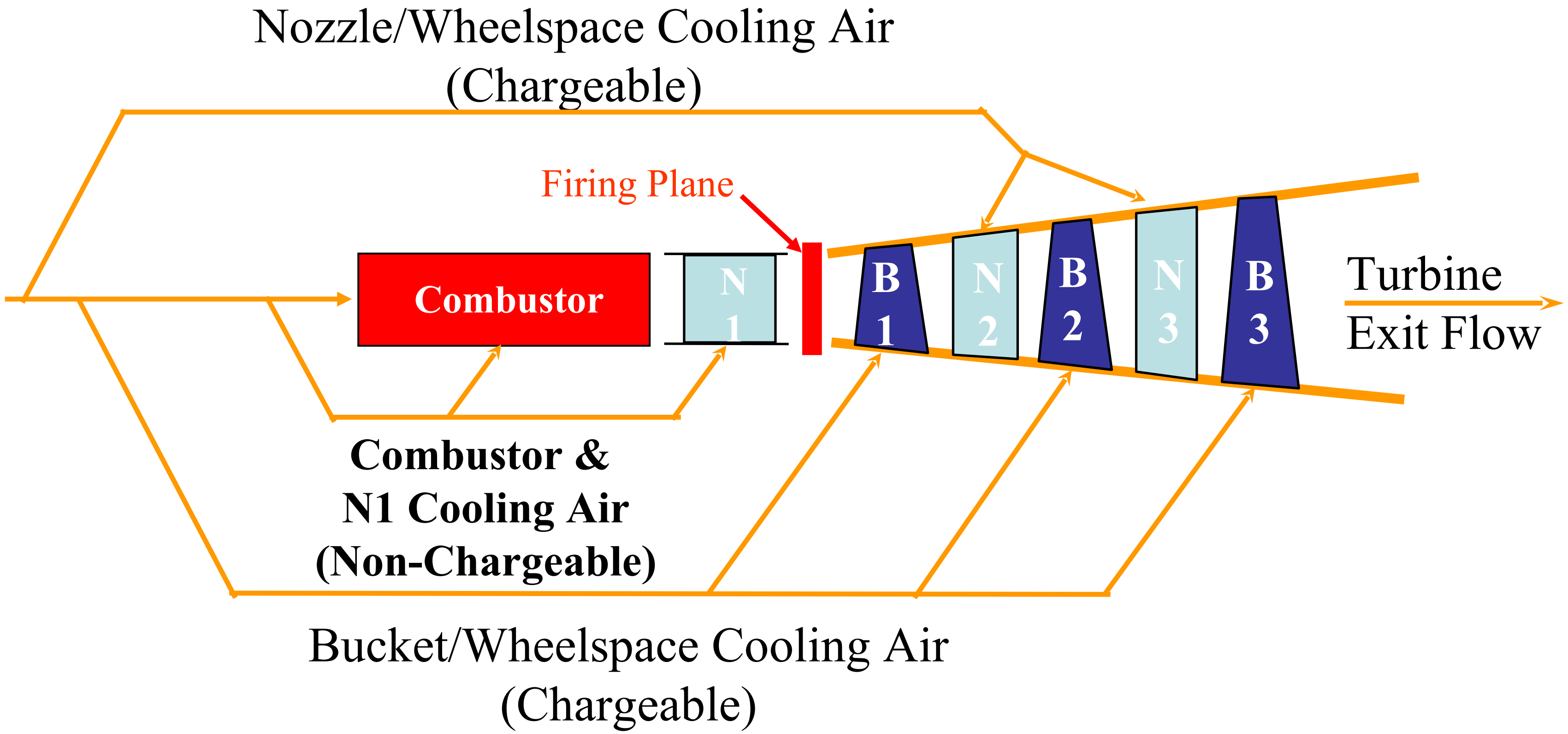


Firing Temperature

- Defined as gas temp at point in cycle where initiation of turbine work begins (N1 trailing edge / B1 leading edge)
- Highest temp point in cycle for thermal performance, but not hottest point in cycle
- Not possible to measure precisely
- Usually the “target parameter” for T_x control curve generation, but not always

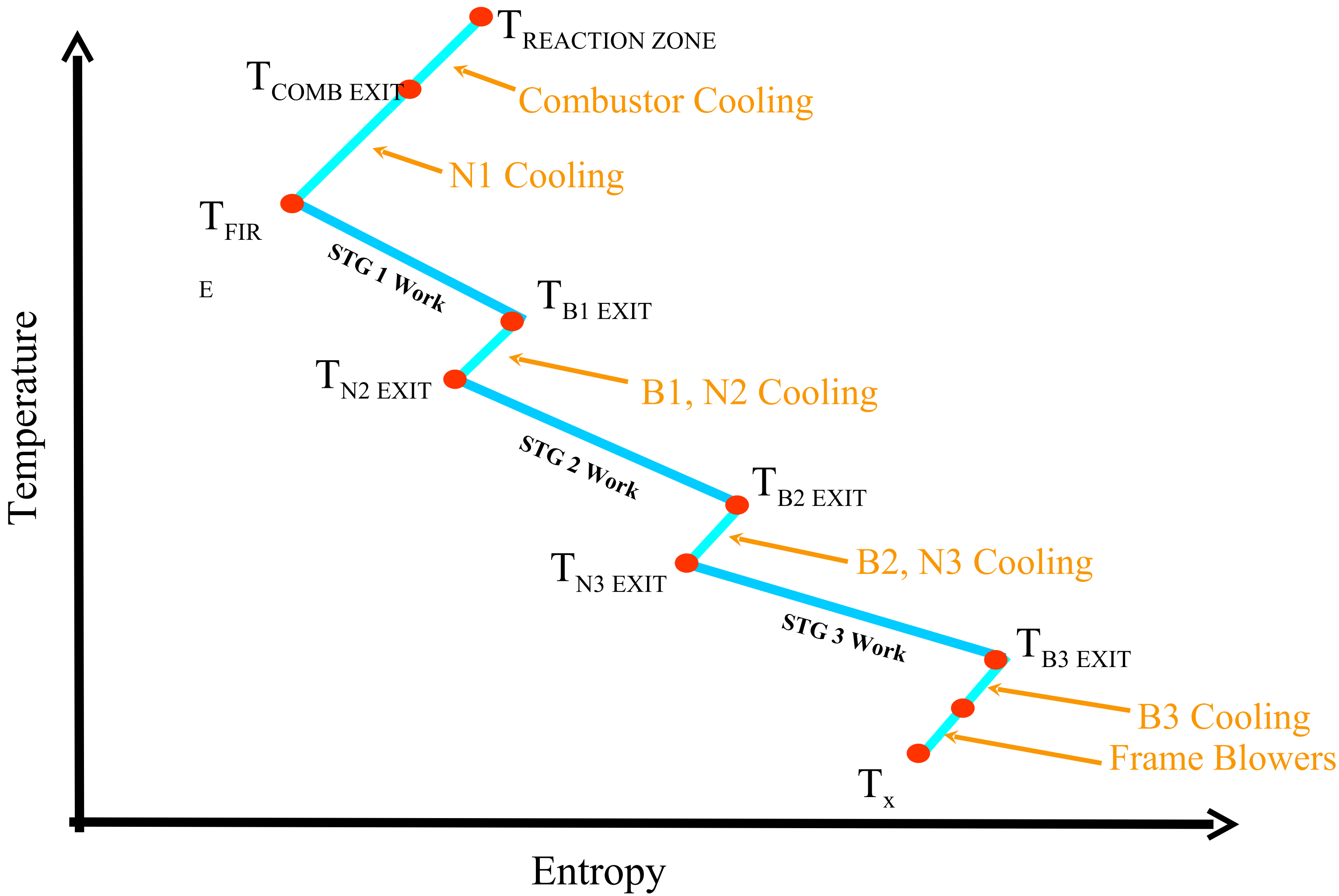
Firing Temperature

Defined at N1 Trailing Edge



Expansion Line

Turbine Cooling Air (Chargeable vs Non-Chargeable)



Temperature Control Curve

- T_x control used to regulate fuel flow such that gas temps/parts lives conform to design basis
- Subject to knowledge of turbine efficiency, turbine cooling flows, back pressure
- Can have separate curves for base load, part load
- Can be tailored to achieve variable firing temperature, simultaneously meeting performance, emissions, & parts life goals

Temperature Control Curve

Strategy Based on Turbine Efficiency Equation

Starting From Basic Efficiency Equation:

$$\eta_{\text{turbine}} = \frac{\Delta T}{\Delta T'}$$

Through substitution of thermo & compressible flow principles, then re-arranging terms:

$$T_3 = \frac{T_4}{\left[1 - \eta_{turbine} \left(1 - \frac{1}{\left(\frac{P_3}{P_4} \right)^{\gamma - 1/\gamma}} \right) \right]}$$

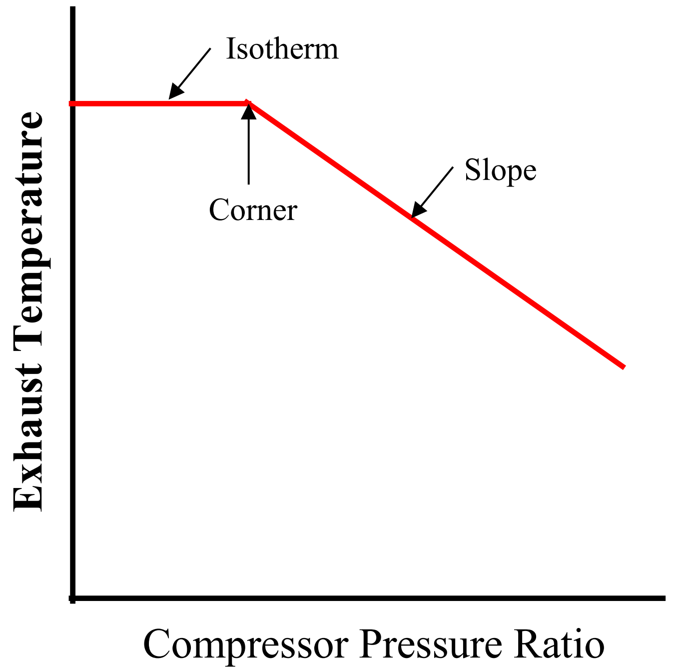
Temperature Control Curve

Design Process

Process Inputs:

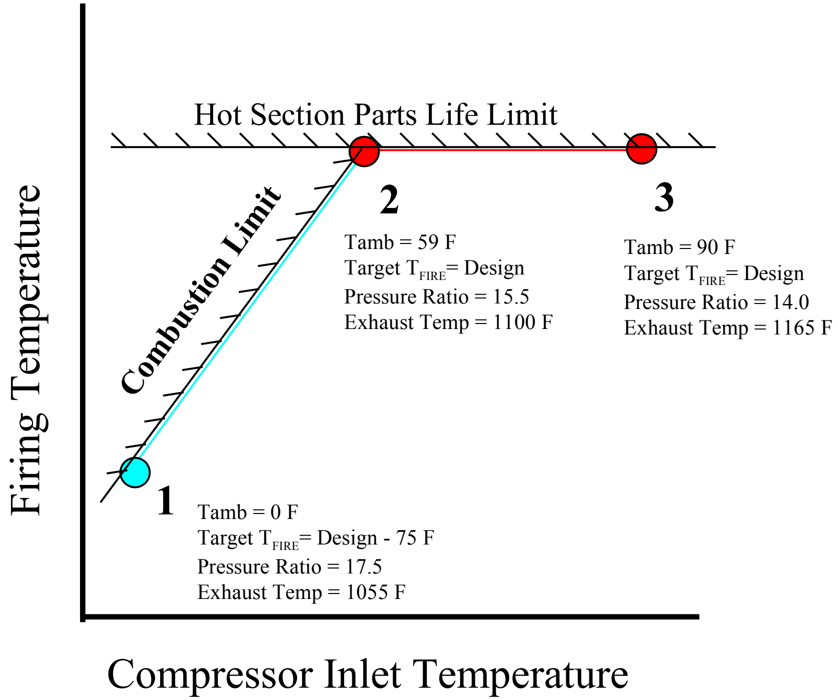
1) Current Cycle Deck
2) Target Firing Temperature
3) Expected Site Ambients
4) Expected Fuel
5) Target N_{OX}
6) T_X Limit
7) "Special" Considerations
   - Tilted Curves
   - 1, 2, 3 Piece
   - Humidity
   - Dry vs Wet
   - DLN T_{RISE} Criteria
   - Base Load vs Part Load
   - Compressor Temp Bias

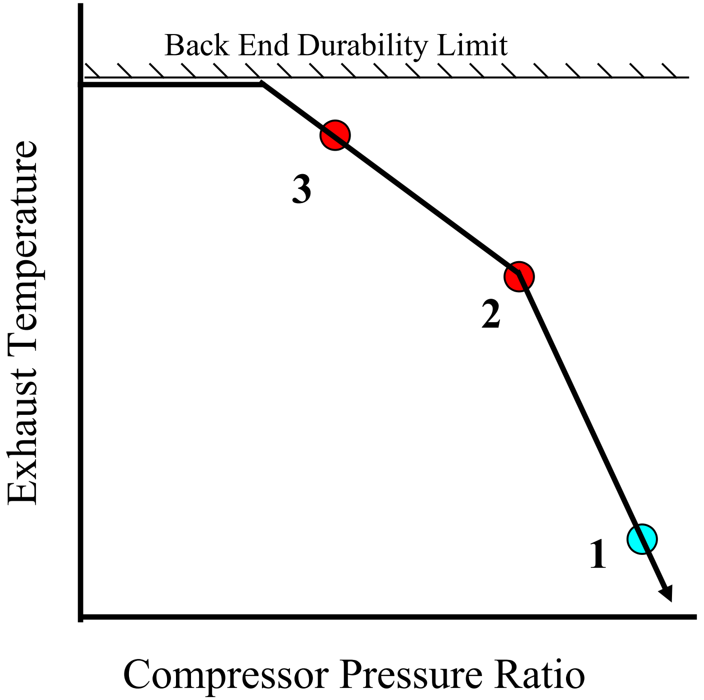
Process Output:



Temperature Control Curve

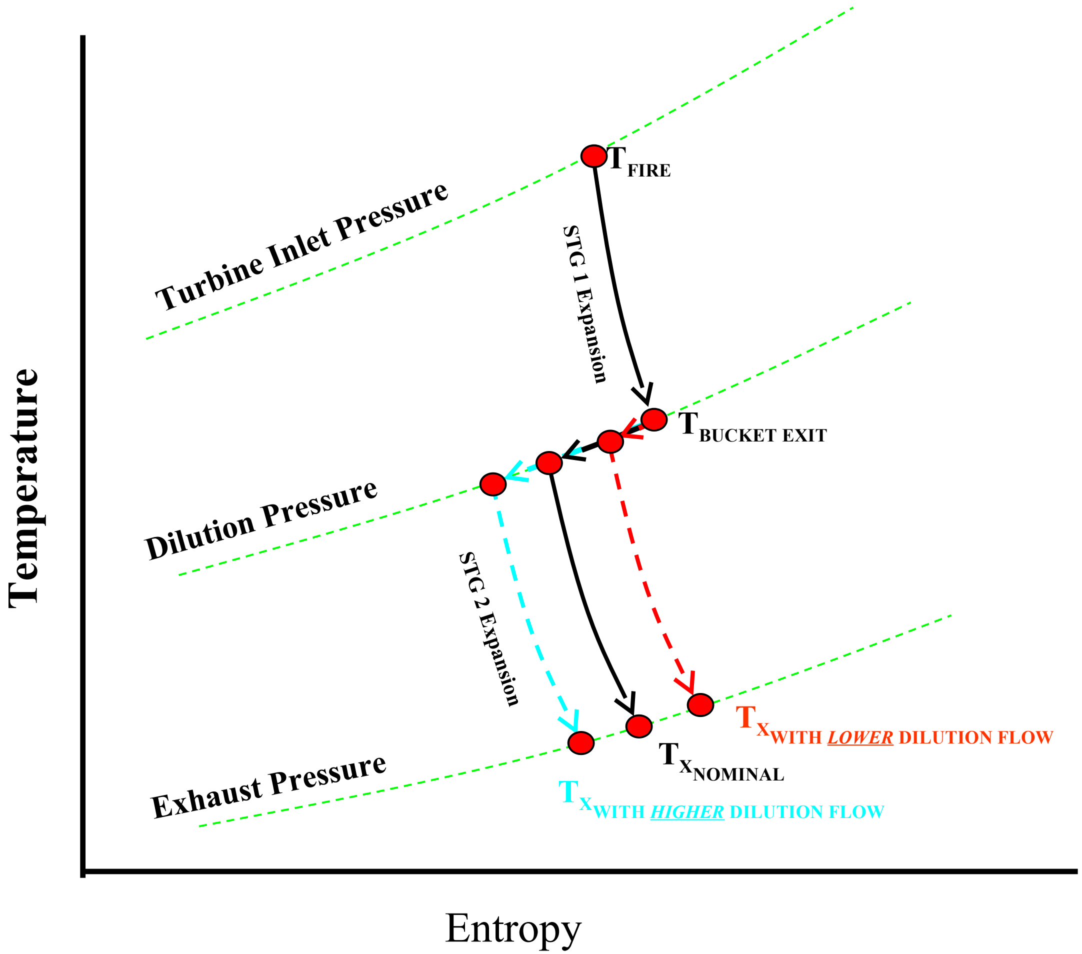
Design Example





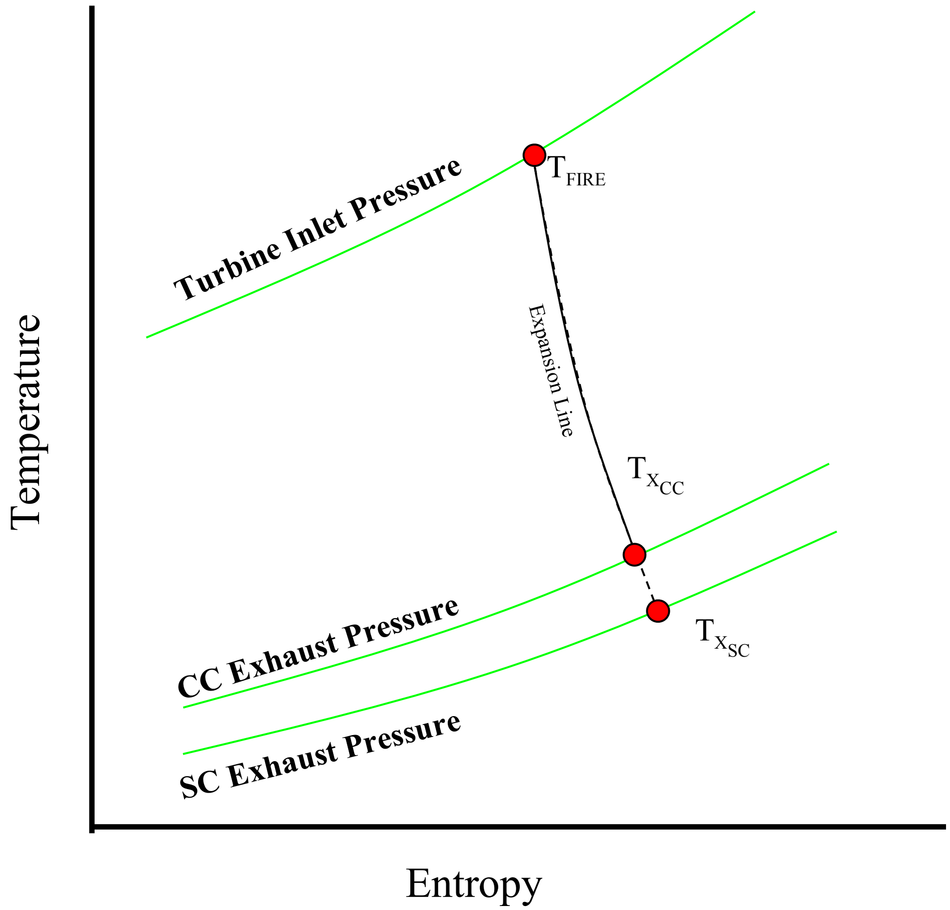
Temperature Control Curve

Dilution Effect



Temperature Control Curve

Backpressure Effect



Wrap - Up

- Brayton Cycle Analysis
  - Higher P/P is Good
  - Higher Firing Temp is Good
  - Cycle Inefficiencies, DP's, Turbine Cooling are Bad

- Cycle Deck
  - Modular Design, Evolves Over Time
  - #1 Performance Tool (Design, Ratings, Control, Monitors)

- Firing Temperature
  - Controlled via Exhaust Temperature
  - Sensitive to hT , Turbine Cooling, Backpressure