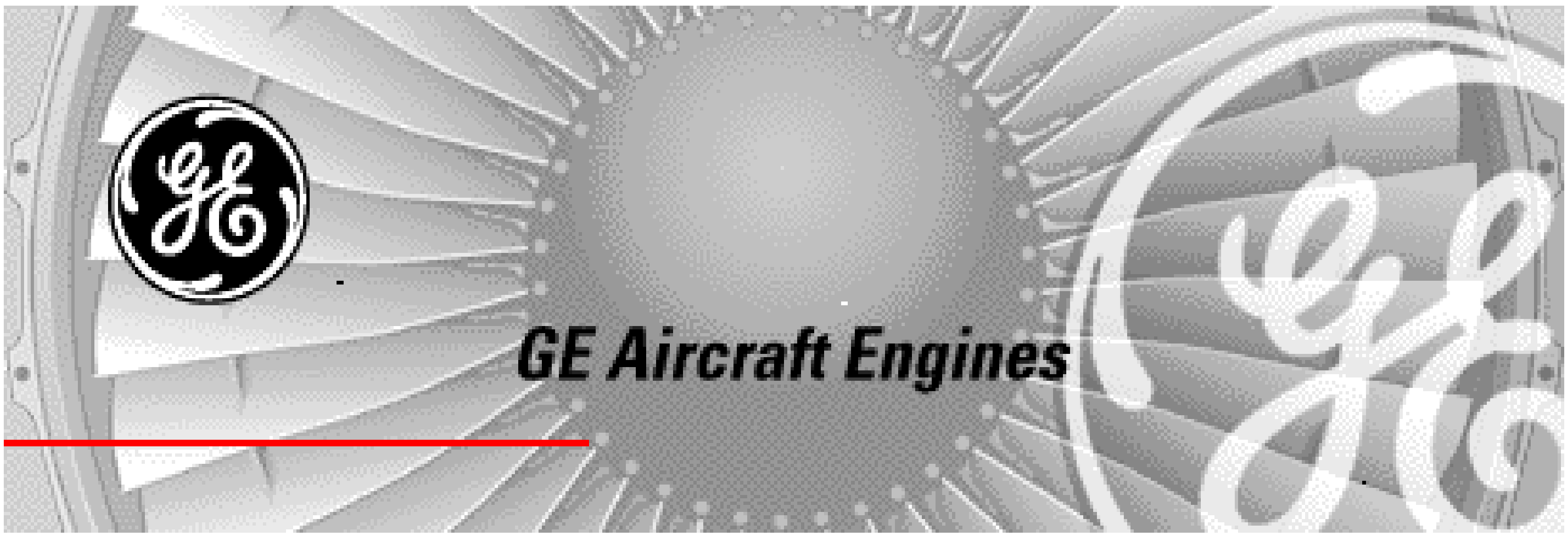
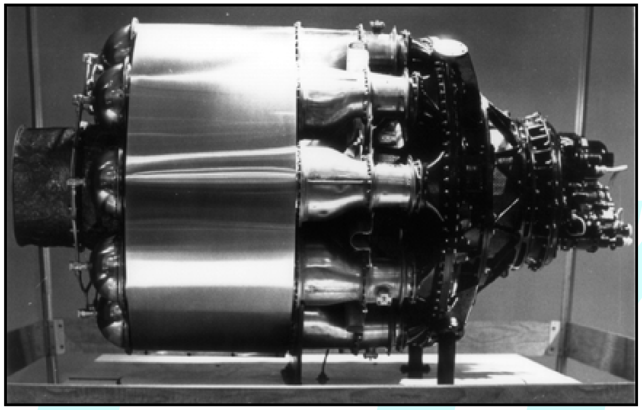
The Aircraft Engine Design Project
Fundamentals of Engine Cycles



Spring 2009

Ken Gould
Phil Weed

GE Aviation Technical History

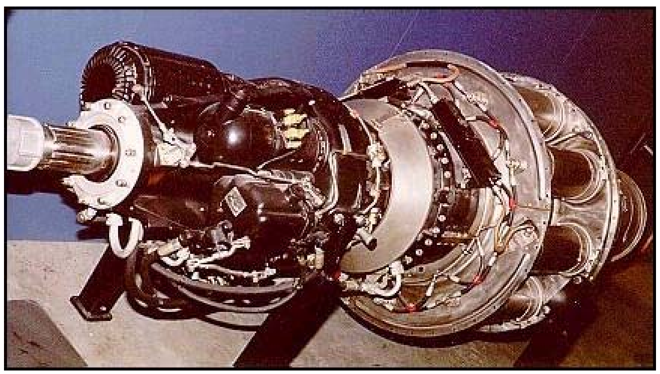


I-A - First U.S. jet engine
(Developed in Lynn, MA, 1941)

GE90 on test

First

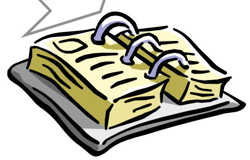
- U.S. jet engine
- U.S. turboprop engine
- Variable stator engine
- Mach 2 fighter engine
- Mach 3 bomber engine
- High bypass engine
- Variable cycle turbofan engine
- Unducted fan engine
- 30:1 pressure ratio engine
- Demonstration of 100k+ engine thrust
- Certified double annular combustor engine



First U.S. turboprop powered aircraft, Dec. 1945

Flowdown of Requirements

The Customer: Overall system requirements
MTOW, Range, Cost per seat per mile



The Airframer: Sub-system requirements
Technical: Wing (lift/drag),**Engines**(Thrust/SFC)
Program: Cost and Schedule

FAA/JAA
Safety/reliability
Noise/emissions

Engines Systems: Module requirements
Technical: Pressure ratio, efficiency, weight, life
Program: NRE, part cost, schedule, validation plan

Design & Validation

Qualified Product

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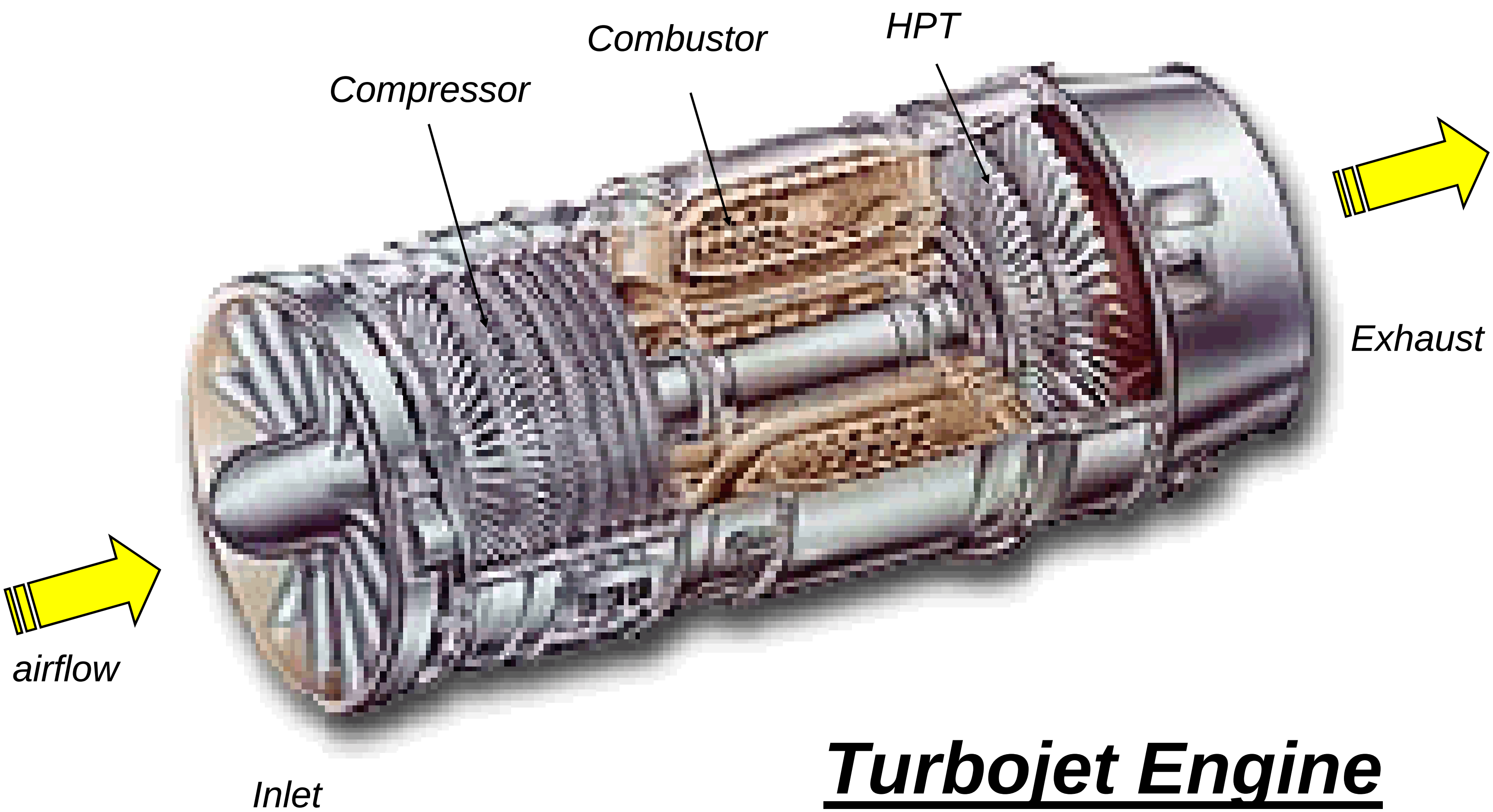
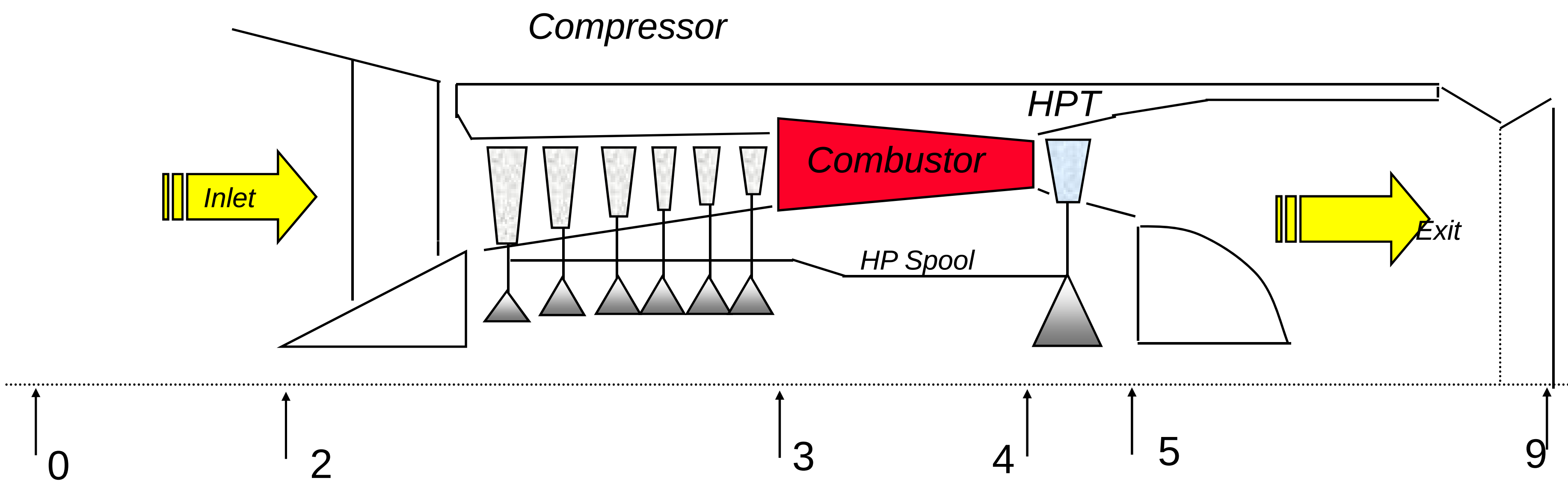


Turbojet Engine

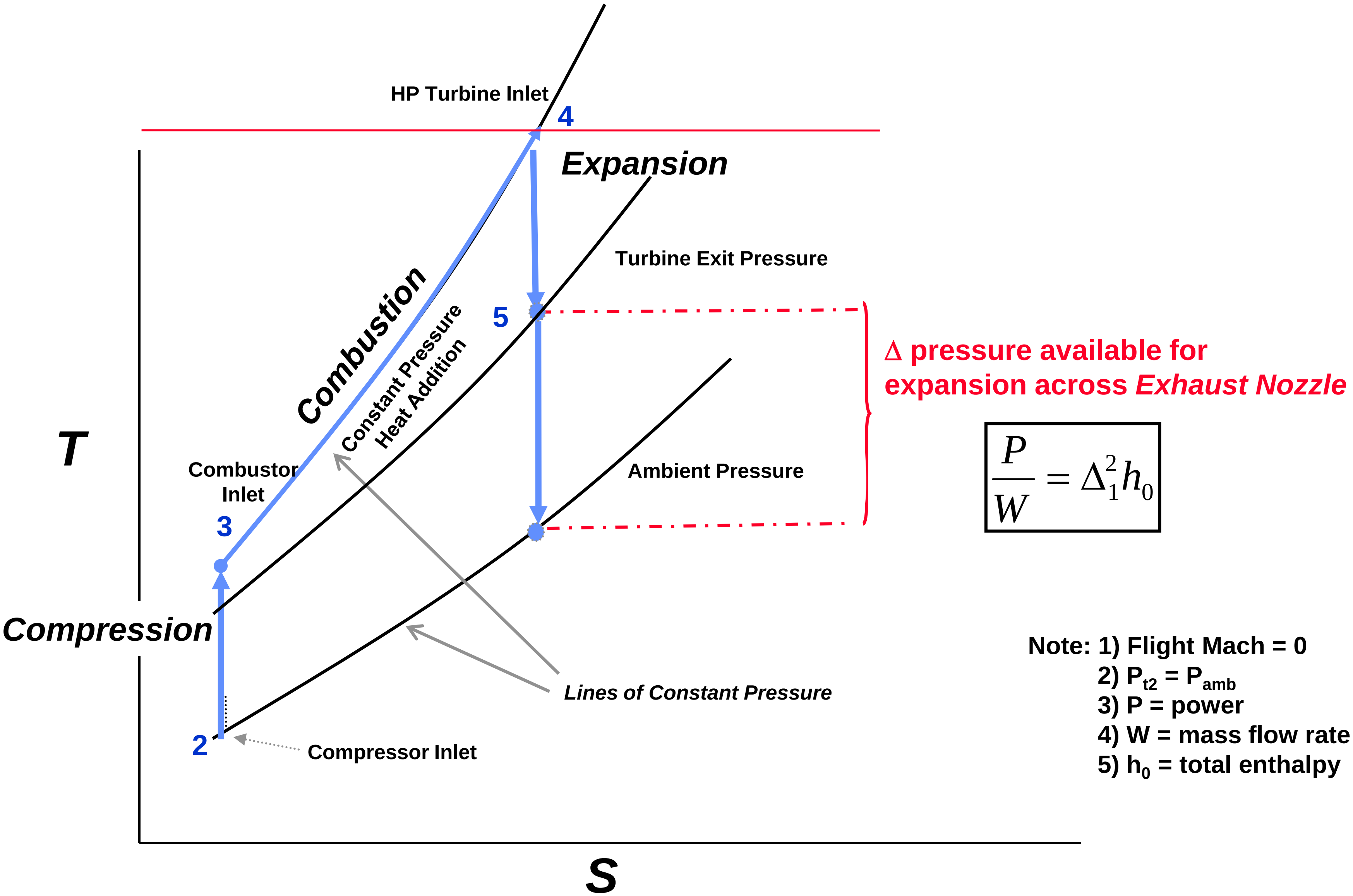
Engine Modules and Components



Turbojet Engine Cross-Section

Multi-stage compressor module powered by a single stage turbine

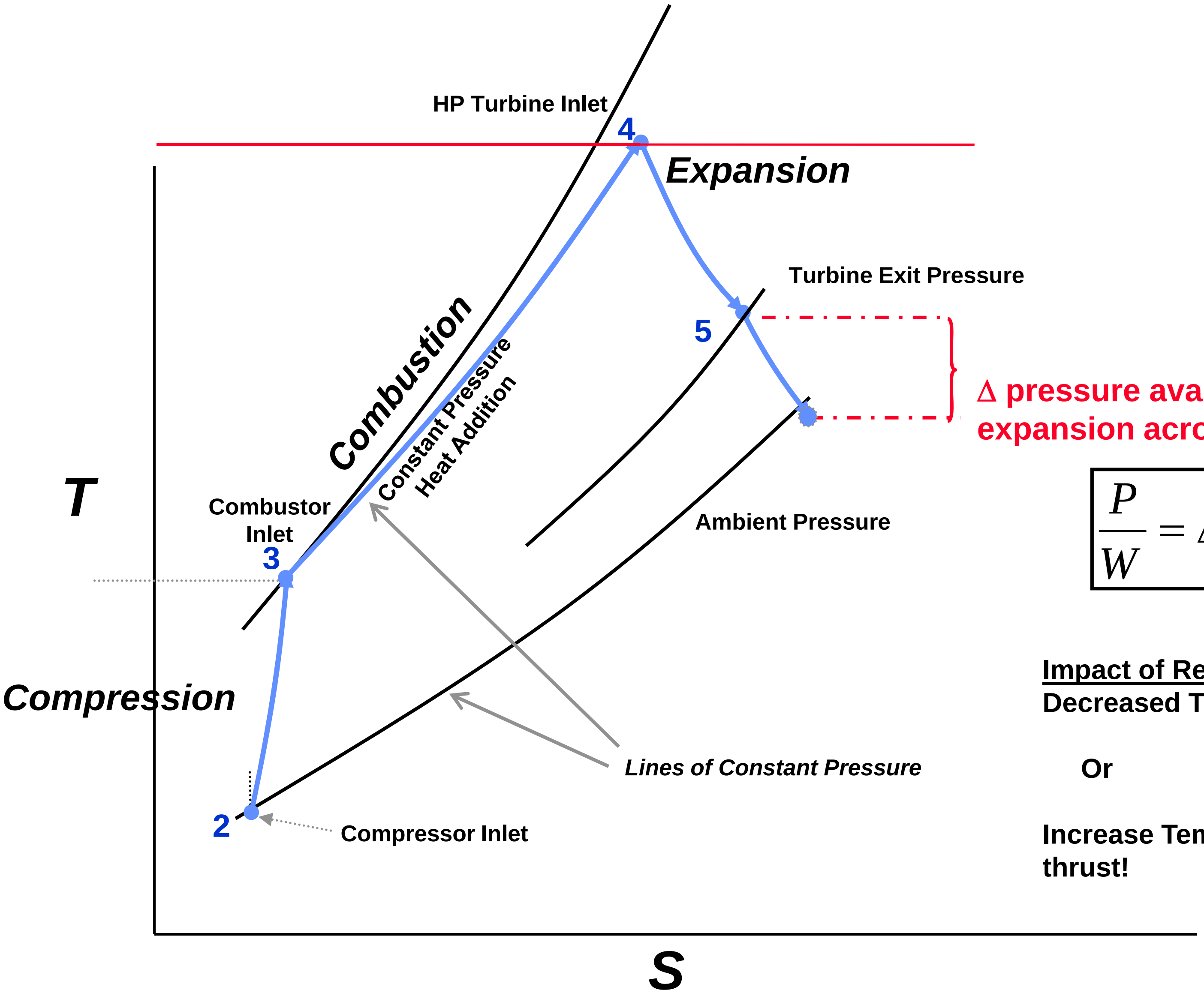
Ideal Brayton Cycle: T-S Representation



$$\boxed{\frac{P}{W} = \Delta_1^2 h_0}$$

Note: 1) Flight Mach = 0
2) $P_{t2} = P_{amb}$
3) P = power
4) W = mass flow rate
5) h_0 = total enthalpy

Real Brayton Cycle: T-S Representation



Δ pressure available for expansion across *Exhaust Nozzle*

$$\boxed{\frac{P}{W} = \Delta_1^2 h_0}$$

Impact of Real Efficiencies:
Decreased Thrust @ if T4 is maintained

Or

Increase Temp (fuel flow) to maintain thrust!

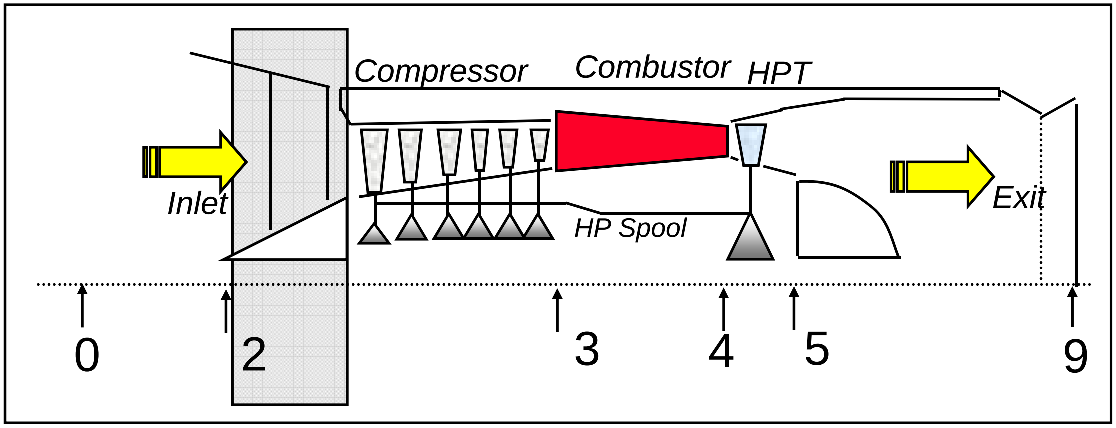
Engine Inlet

- Flow capacity (flow function relationship)
  Starting with the conservation of mass and substituting the total to static relations for Pressure and Temperature, can derive:
  W= Density * Area* Velocity

$$\frac{W^*(\mathrm{sqrt}(Tt))}{Pt^*\ Ae} = \frac{M\ {}^*\mathrm{sqrt}(g_c{}^*\gamma/R)}{[1+((\gamma-1)/2)^*M^2]^{(\gamma+1)/[2^*(\gamma-1)]}}$$

where M is Mach number
Tt is total temperature (deg R)
Pt is total pressure (psia)
W is airflow (lbm/sec)
Ae is effective area (in^2)
gc is gravitational constant
=32.17 lbm ft/(sec^2 lbf)
γ is ratio of specific heats
R is gas constant
(ft-lbf)/(lbm-deg R)

Turbojet



Compressor

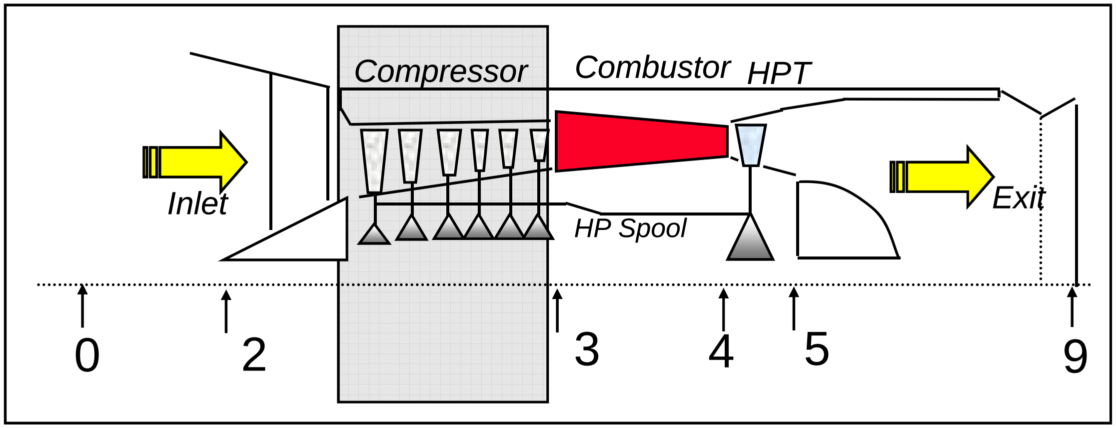
• From adiabatic efficiency relationship

$$\eta_{compressor} = \text{Ideal Work/ Actual Work} = \frac{Cp^*(Texit' - Tinlet)}{Cp^*(Texit - Tinlet)}$$

$$= \frac{(Pexit/Pinlet)^{(\gamma-1)/\gamma} - 1}{Texit/Tinlet - 1}$$

where
Pexit is compressor exit total pressure (psia)
Pinlet is compressor exit total pressure (psia)
Tinlet is compressor inlet total temperature (deg R)
Texit is compressor exit total temperature (deg R)
Texit' is ideal compressor exit temperature (deg R)

Turbojet



Combustor

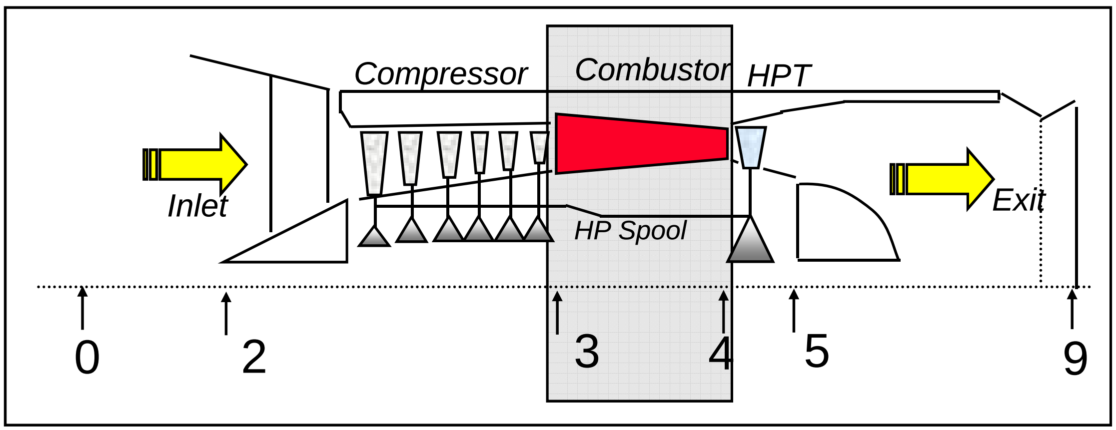
•From Energy balance/ Combustor efficiency relationship:

$$\eta_{combustor} = \text{Actual Enthalpy Rise/ Ideal Enthalpy Rise}$$

$$= \frac{(WF + W)*Cp_{combustor}Texit - W*Cp_{combustor}Tinlet}{WF * FHV}$$

where W is airflow (lbm/sec)
WF is fuel flow (lbm/sec)
FHV is fuel heating value (BTU/lbm)
T_{inlet} is combustor inlet total temperature (deg R)
T_{exit} is combustor exit total temperature (deg R)
Cp is combustor specific heat
BTU/(lbm-deg R)
Can express WF/W as
fuel to air ratio (FAR)

Turbojet



Turbine

- From efficiency relationship

$$\eta_{turbine} = \text{Actual Work/Ideal Work} = \frac{Cp^*(Tinlet - Texit)}{Cp^*(Tinlet - Texit')}$$

$$= \frac{1 - (Texit/Tinlet)}{1 - (Pexit/Pinlet)^{(\gamma-1)/\gamma}}$$

- Work Balance: From conservation of energy

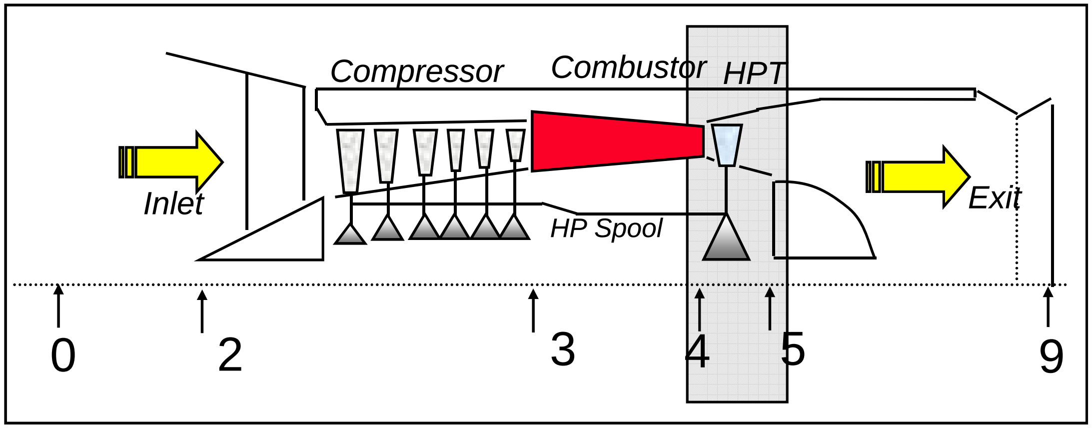
Turbine Work = Compressor Work + Losses

$$(W+ WF)^* Cp_{turb}{}^* (Tinlet - Texit)|_{turb} = W * Cp_{compressor}{}^* (Texit - Tinlet)|_{comp}$$

where

Pexit is turbine exit total pressure (psia)
Pinlet is turbine exit total pressure (psia)
Tinlet is inlet total temperature (deg R)
Texit is exit total temperature (deg R)
Texit' is ideal exit total temperature (deg R)
Cp is specific heat for turbine or compressor BTU/(lbm-deg R)

Turbojet



Nozzle

- Isentropic relationship, can determine exhaust properties

$$Tt/Ts = (Pt/Ps)^{(\gamma-1)/\gamma}$$

$$= 1 + ((\gamma - 1)/2) * M^2$$

- From Mach number relationship can determine exhaust velocity

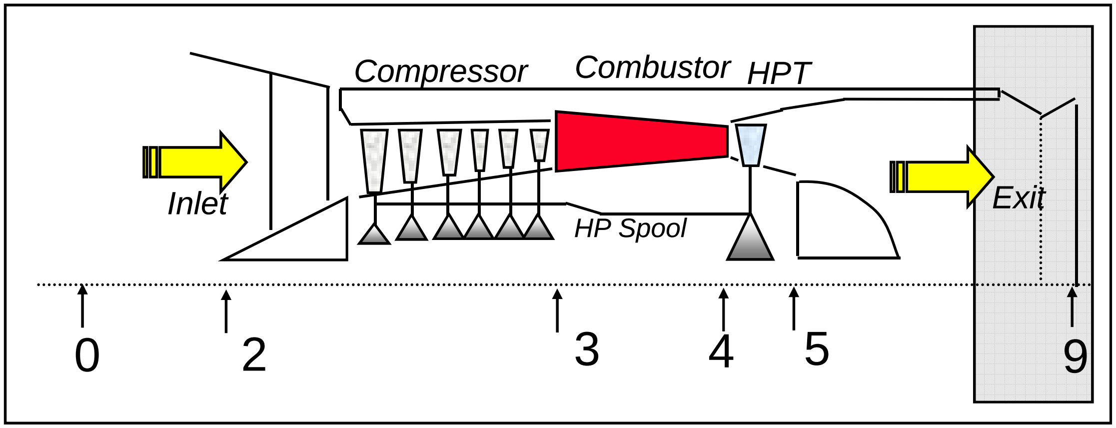
$$v = M*a$$

where a, speed of sound= $\mathrm{sqrt}(\gamma * g_c * R * Ts)$

where

Tt is total temperature (deg R)
Pt is total pressure (psia)
Ps is static pressure (psia)
Ts is static temp (deg R)
g_c is gravitational constant
=32.17 lbm ft/(sec^2 lbf)
γ is ratio of specific heats
R is gas constant (ft-lbf)/(lbm-deg R)
v is flow velocity (ft/sec)
a is speed of sound (ft/sec)
M is Mach number

Turbojet



Engine Performance

- Thrust relationship: from conservation of momentum

$$Fnet = W9\ V9/\ g_c\ -\ W0\ V0/\ g_c\ +\ (Ps9-Ps0)\ A9$$

If flight Mach number is 0, v0 = 0

and if nozzle expands to ambient, PS9=Ps0 and

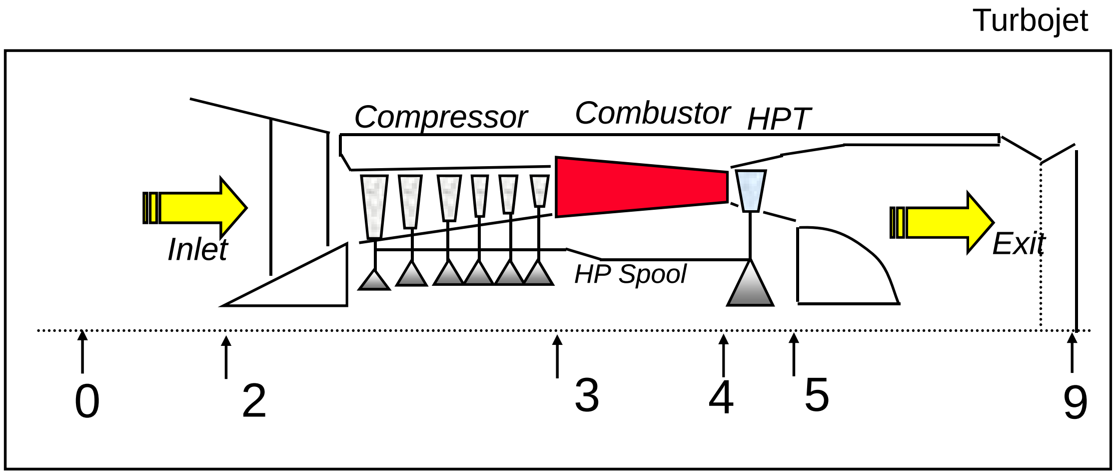
$$Fnet\ = W9\ V9/\ g_c$$

where g_c is gravitational constant

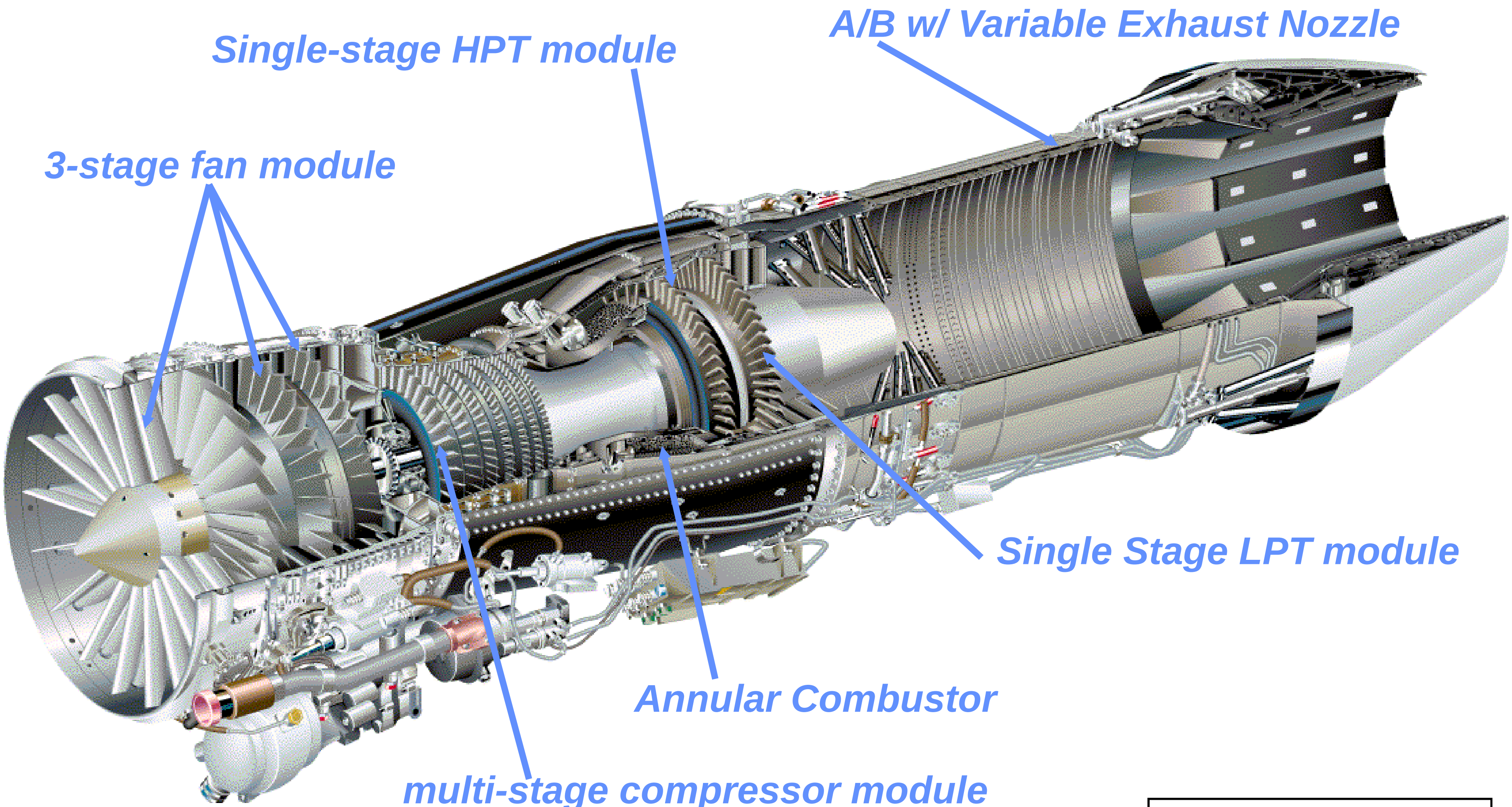
- Specific Fuel Consumption (SFC)

SFC = Wf/ Fnet (lbm/hr/ lbf)

(lower SFC is better)



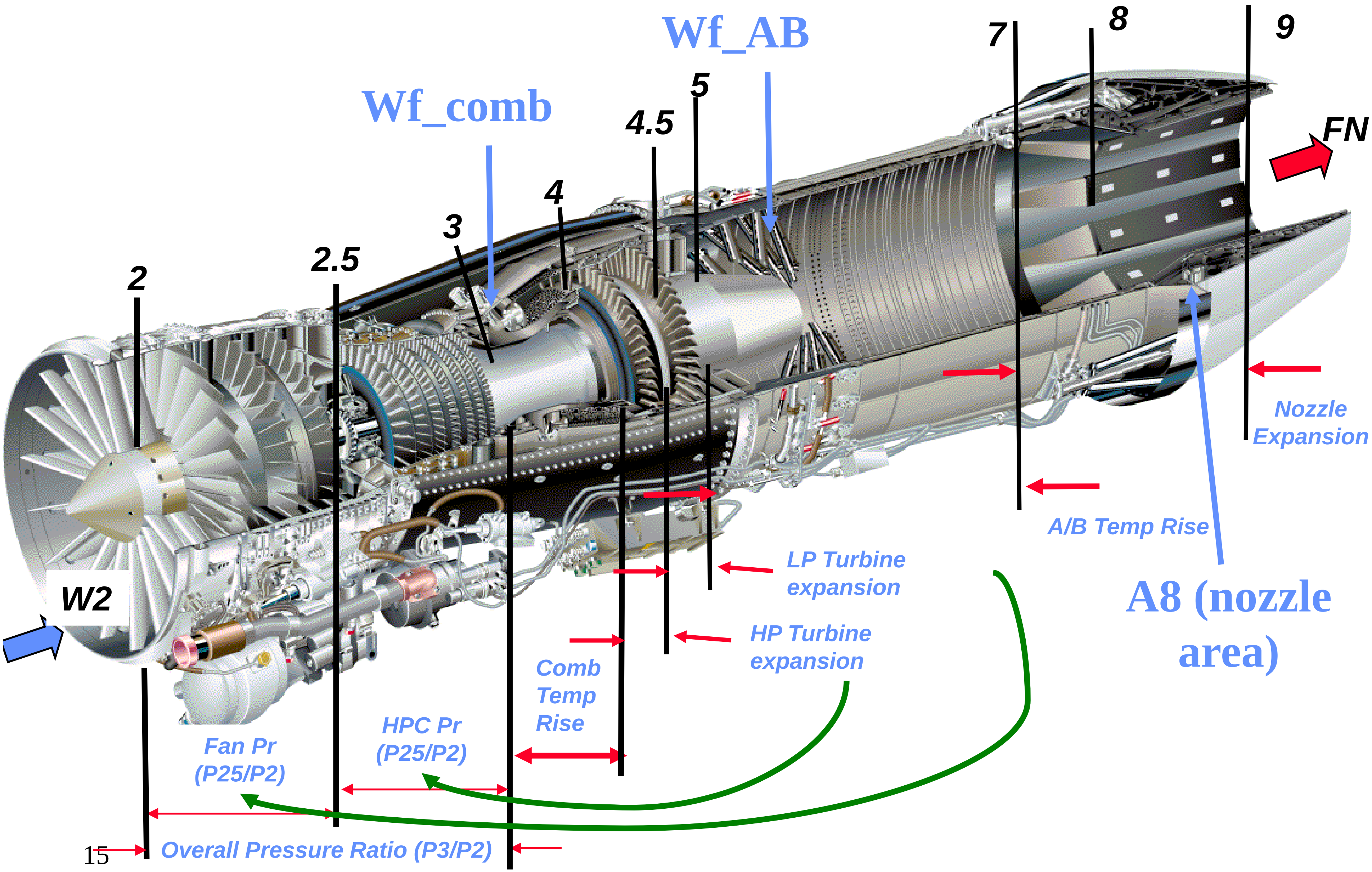
Modern Afterburning Turbofan Engine

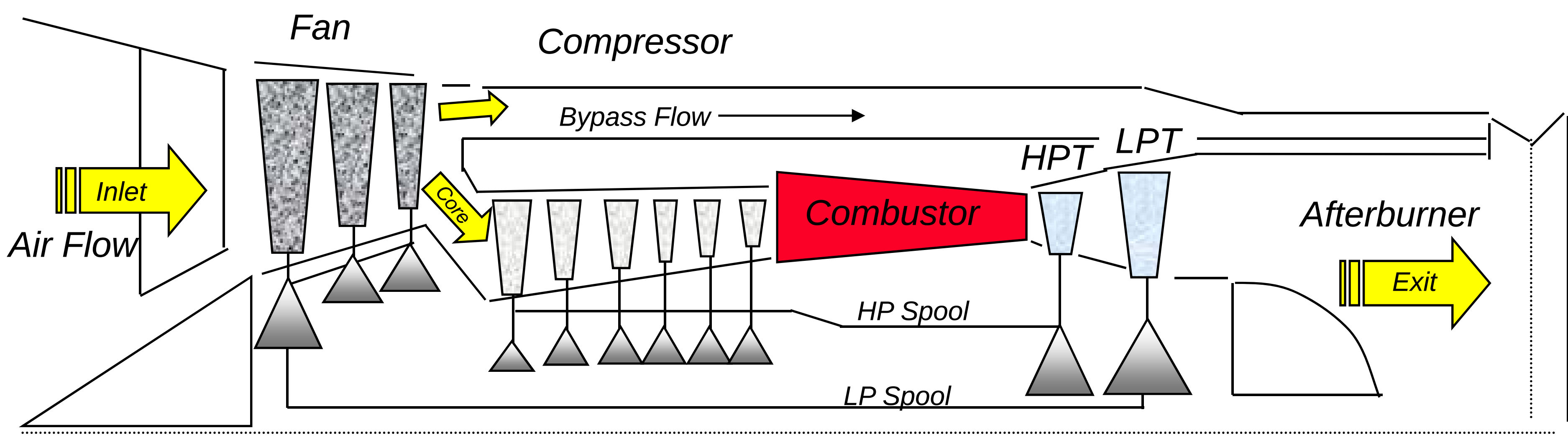


Terms:	
blade	rotating airfoil
vane	static airfoil
stage	rotor/stator pair
PLA	pilot's throttle

Typical Operating Parameters:	
OPR	25:1
BPR	0.34
ITT	2520^{o}F
Airflow	142 lbm/sec
Thrust Class	16K-22K lbf

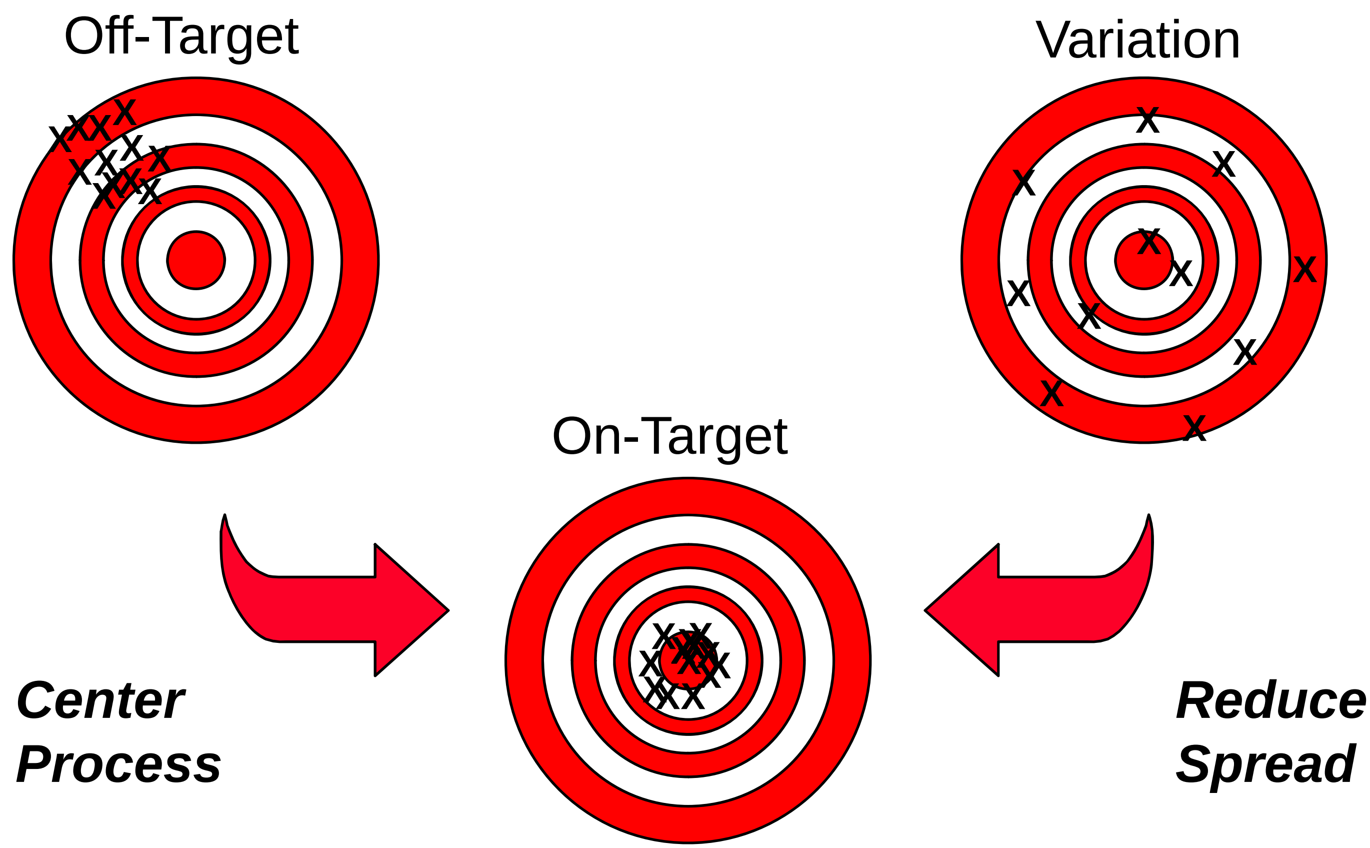
Thermodynamic Station Representation





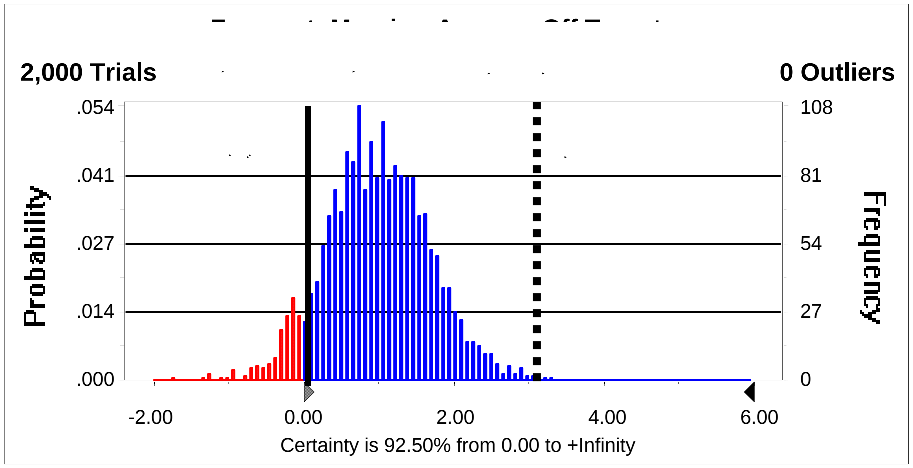
Augmented Turbofan Engine Cross-Section

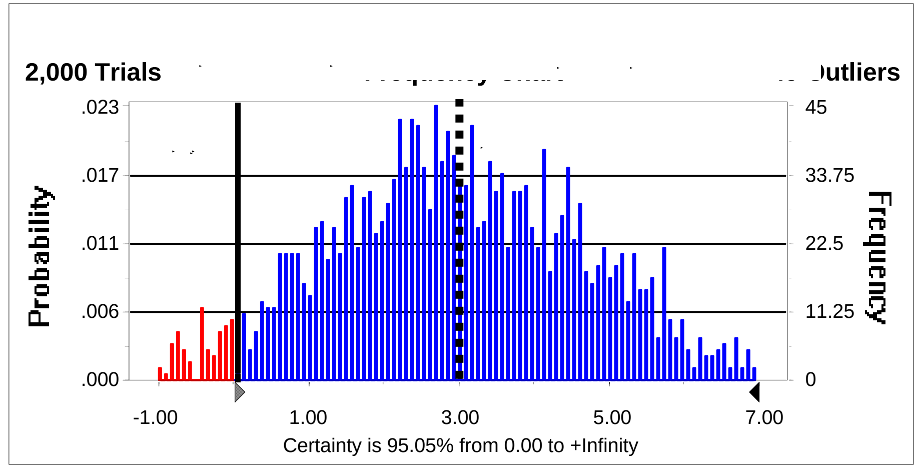
Design Considerations- Process Centering and Variation



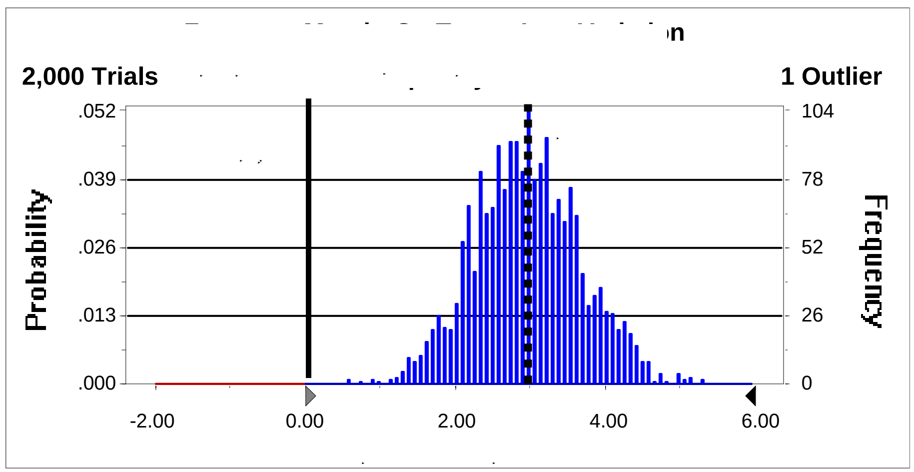
Six Sigma Methodology Applies Statistical Analyses to Center Processes and Minimize Variation

Probabilistic Design Techniques Account for Process Variation





Center Process



Reduce Spread

Understanding and Accounting for Process Variation Assures Compliance with Design Limits