RDDM

Research Design Development Management

Turbomachinery Lecture Series

Module 00 – Masters Introduction
Gas Turbine Engine Design & Development

Presented to - Présenté at

Polytechnique Montréal
AER4270: Propulsion Aéronautique
MEC6615: Théorie avancée de turbomoteurs
MEC8250: Turbomachines

Carleton University
AERO 4402: Aerospace Propulsion

05 October 2020 – 05 Octobre 2020

John H. Kidikian, Ph.D., ing.
MDIDS-GT Senior research associate
Adjunct Professor at Polytechnique Montreal: AER4270 & MEC6615
Adjunct Professor at Carleton University: AERO 4402

Déclaration de copyright
Copyright Statement

Some words of wisdom

The most dangerous phrase in the language is, "We've always done it this way."

- Rear Admiral Grace Murray Hopper

If we worked on the assumption that what is accepted as true really is true, then there would be little hope for advance.

- Orville Wright

Some words of wisdom

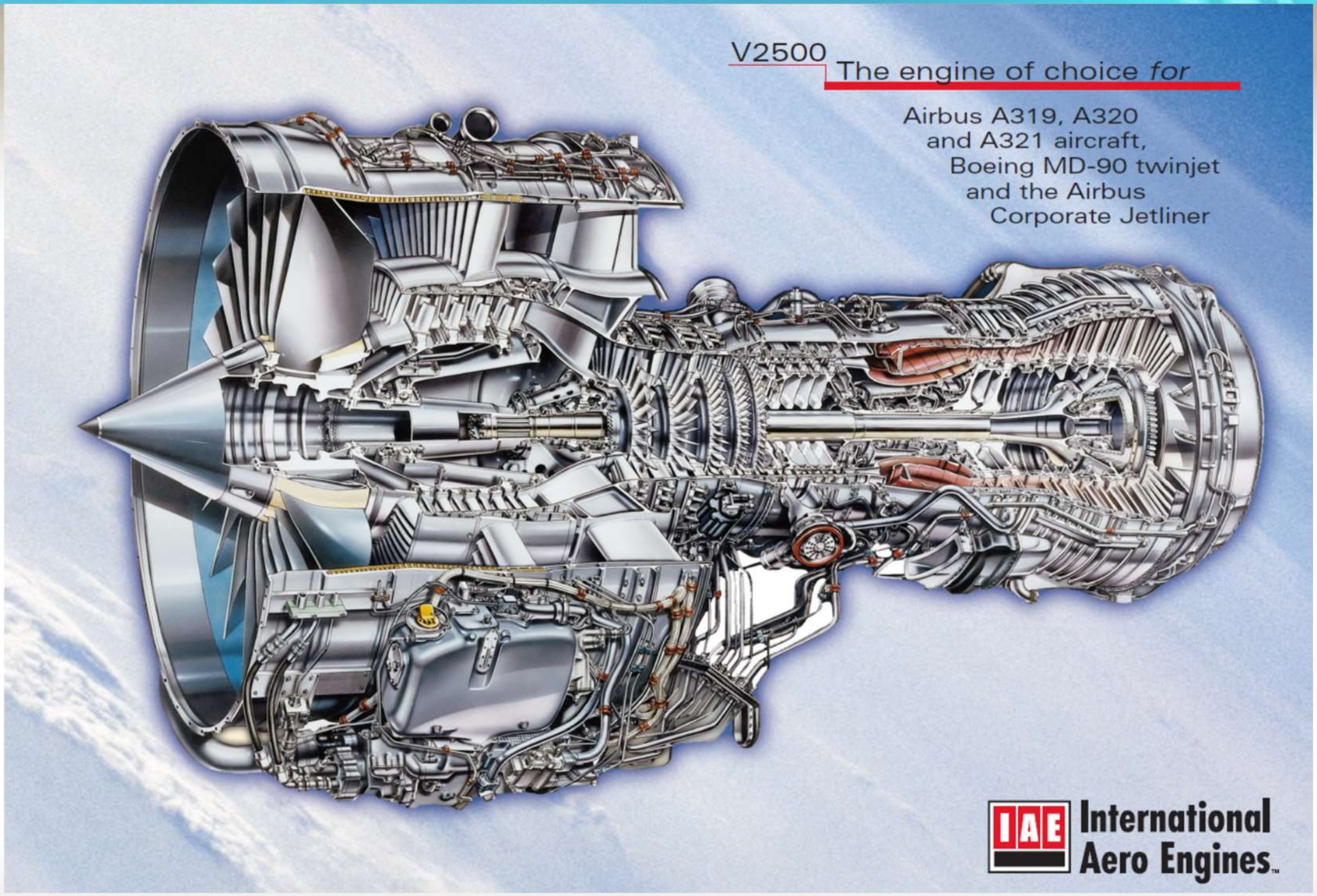
“Simple methods with empirical input are still needed for the mean-line design, and it is often emphasized by experienced designers that if the one-dimensional design is <u>not correct then no amount</u> of CFD will produce a good design”

- Denton

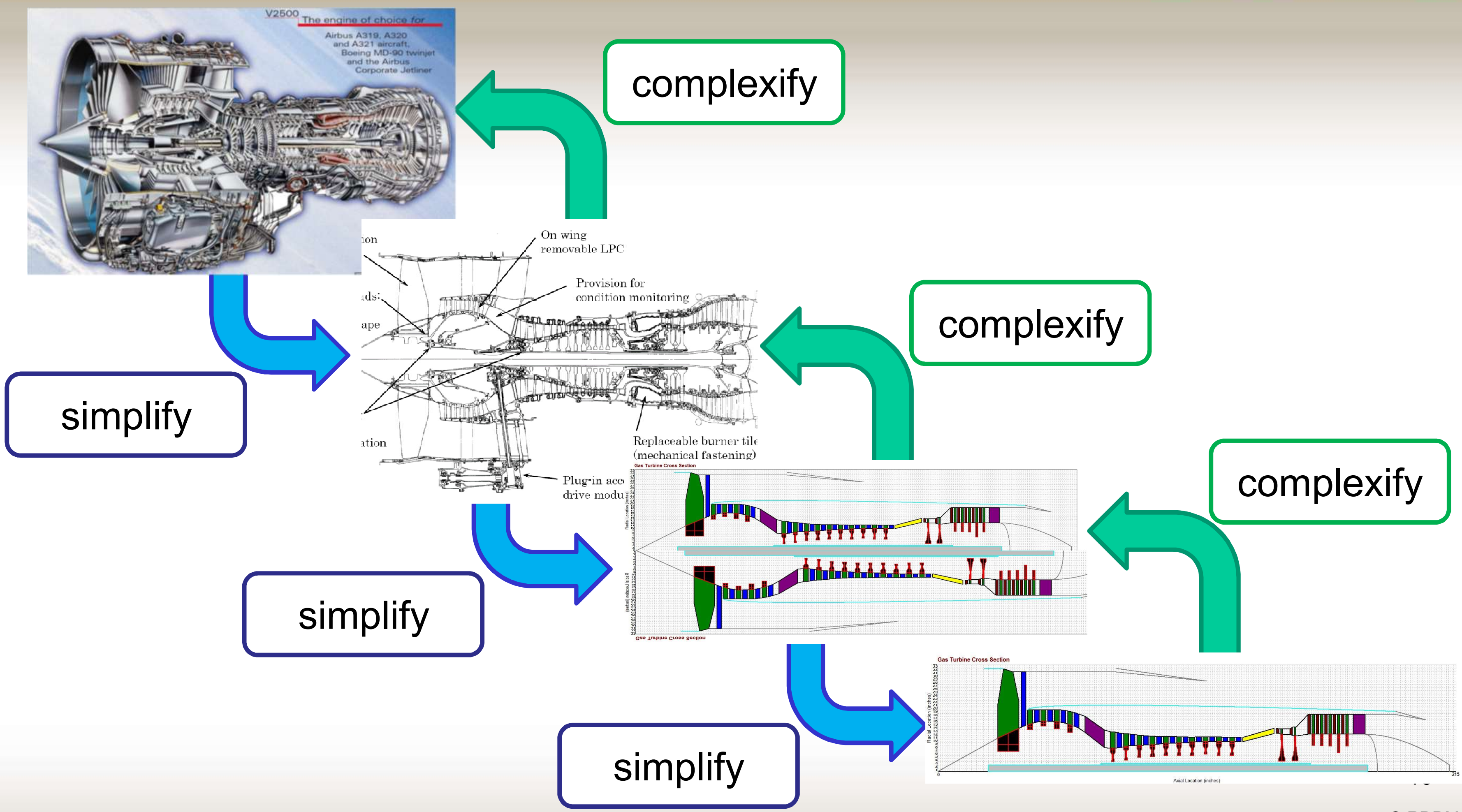
PART ONE

What are we talking about today?

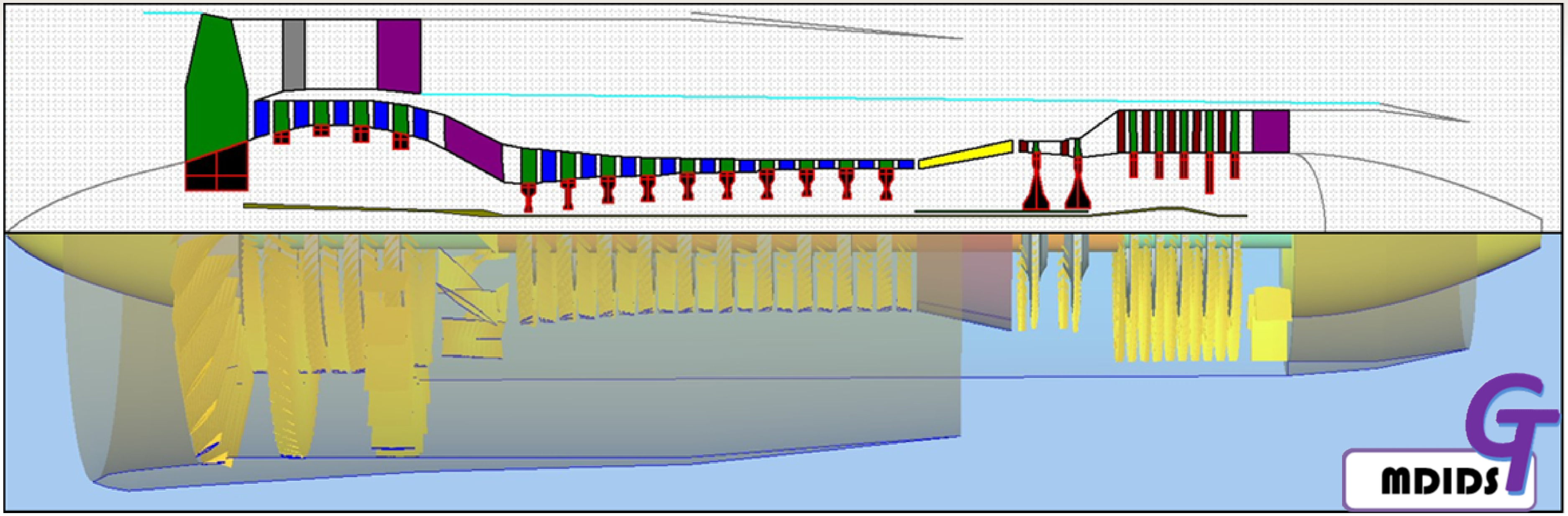
What do we have to do to get to this?



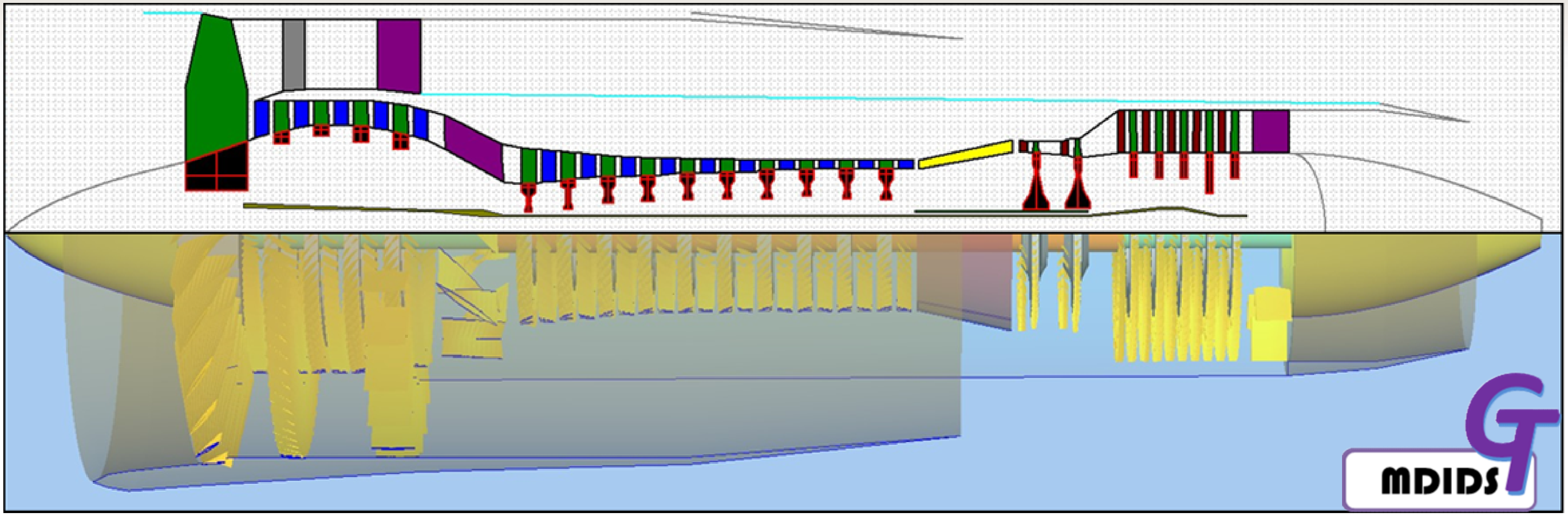
Well, we need to start with the basics



So the idea is to go from a simplified representation to the real thing.

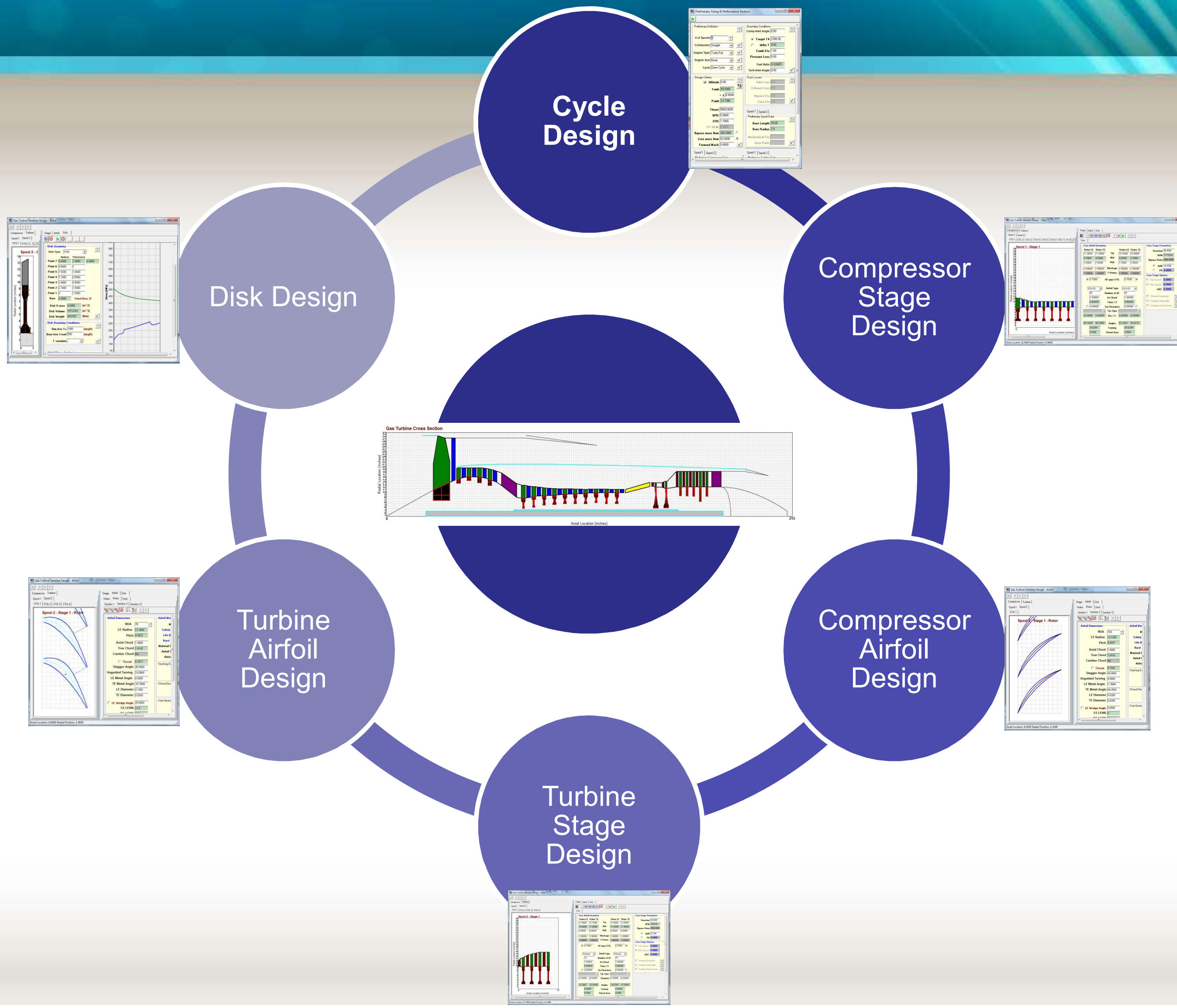


So the idea is to go from a simplified representation to the real thing.

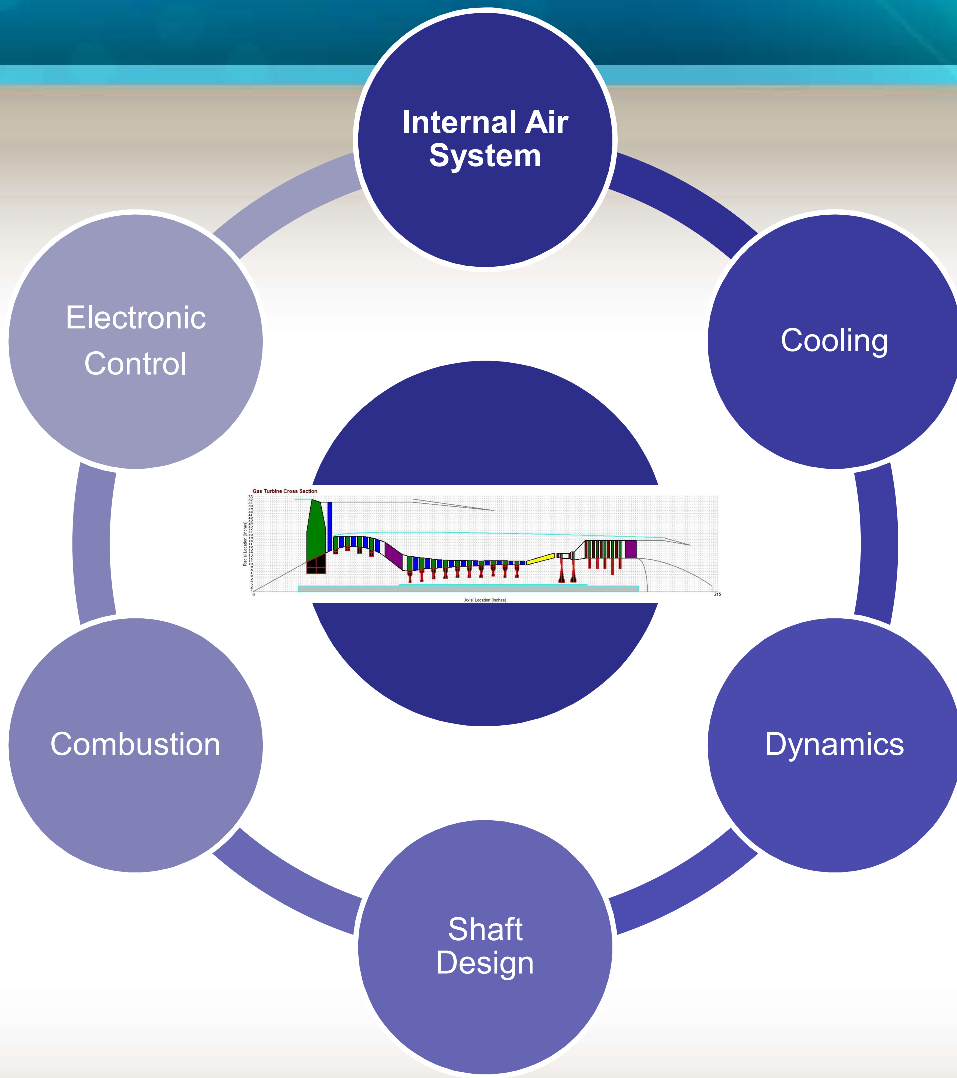


So what do we have to do?

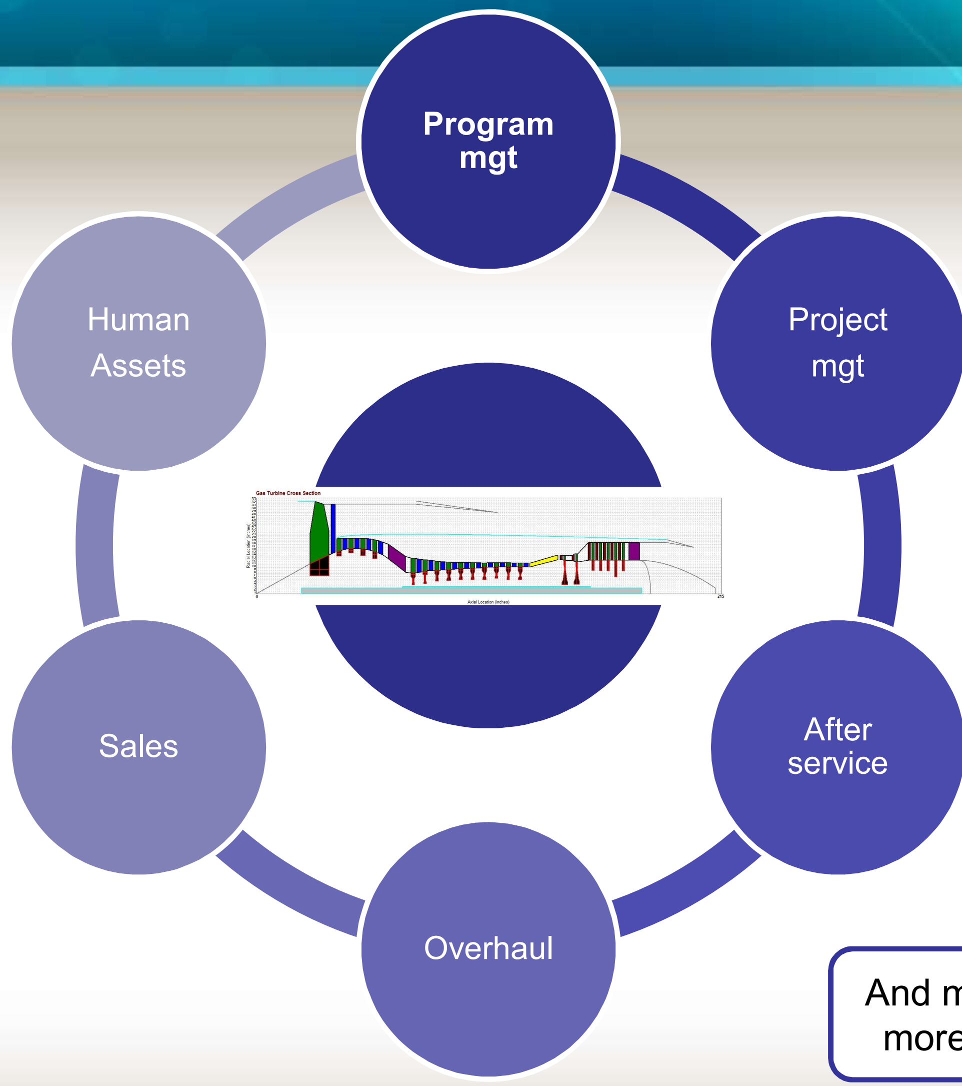
Multi-Disciplinary Design & Optimization



Multi-Disciplinary Design & Optimization (con't)

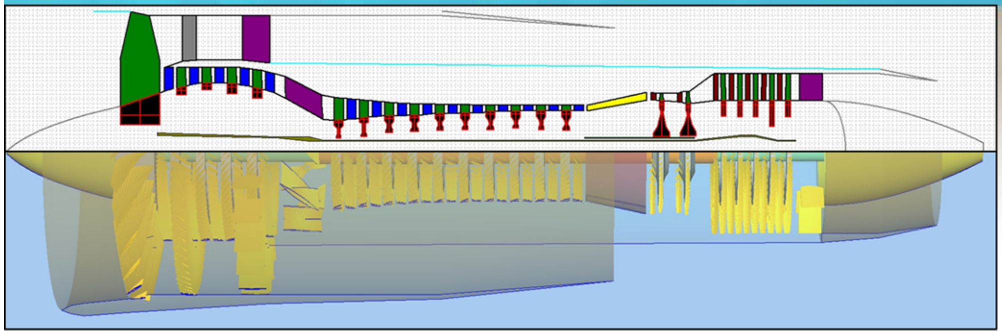


Multi-Disciplinary Design & Optimization (con't)

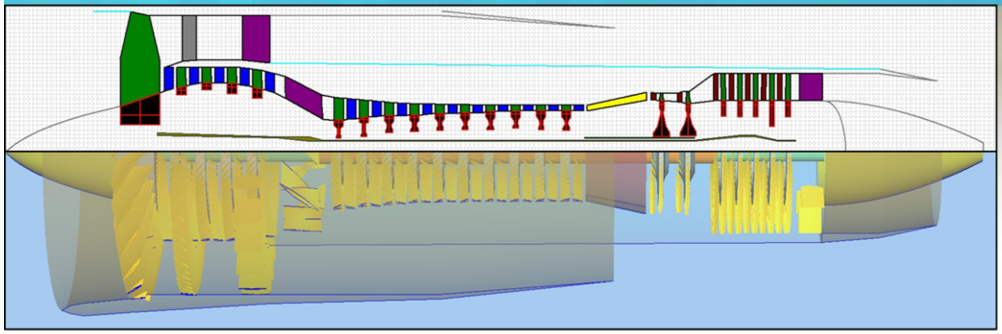


And much more …

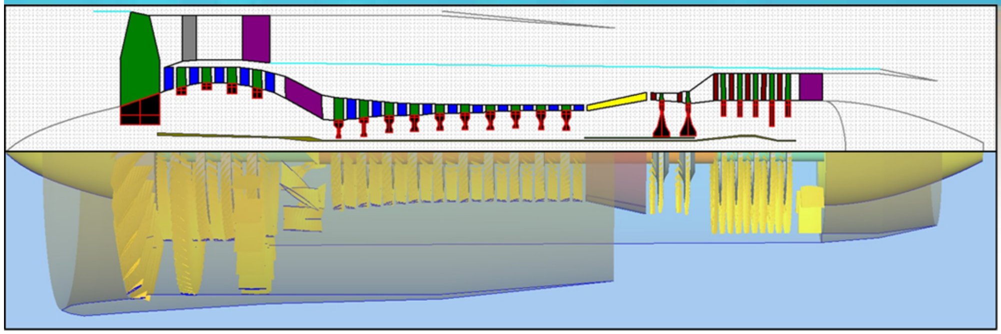
What are the 2 driving constraints?



What are the 2 driving constraints?



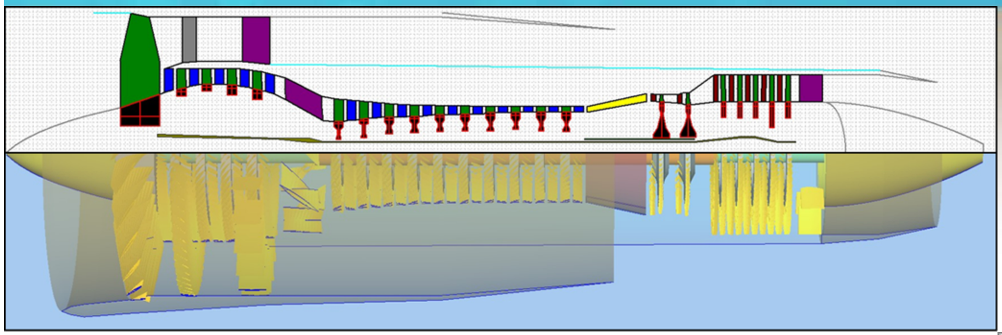
And what is the driving design parameter for a Turbofan?



The driving parameter of Turbofan

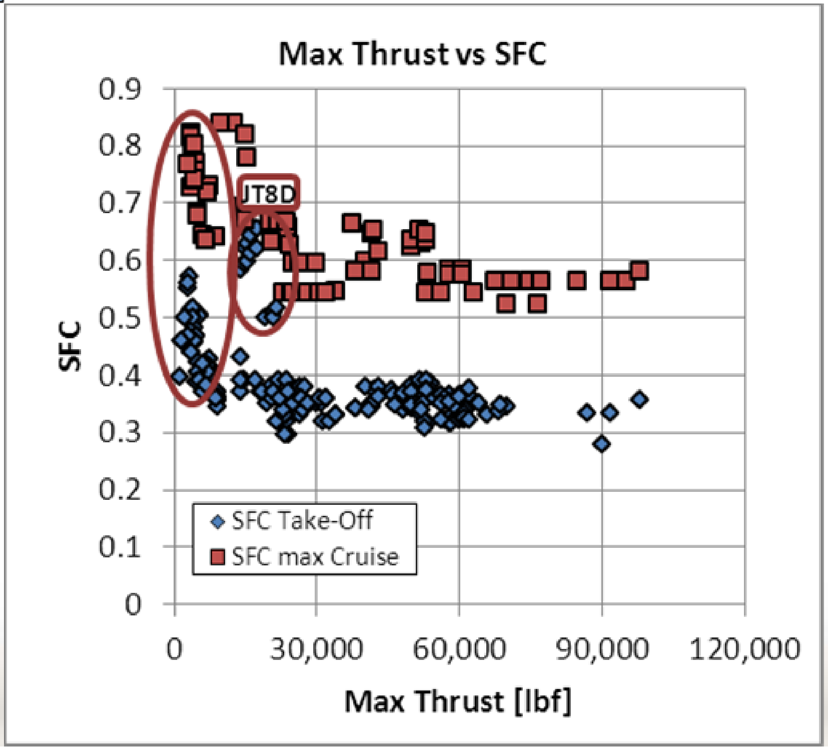
THRUST
IN CONTEXT WITH 60 YEARS OF DATA

It's all about "Thrust"

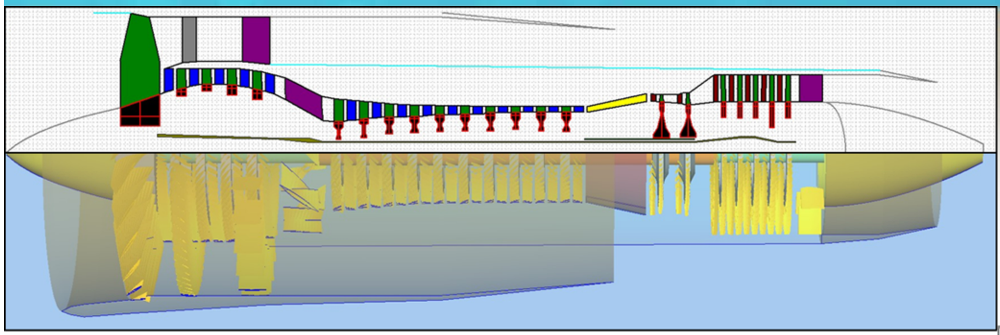


Specific Fuel Consumption (SFC)

Our target to achieve or do better

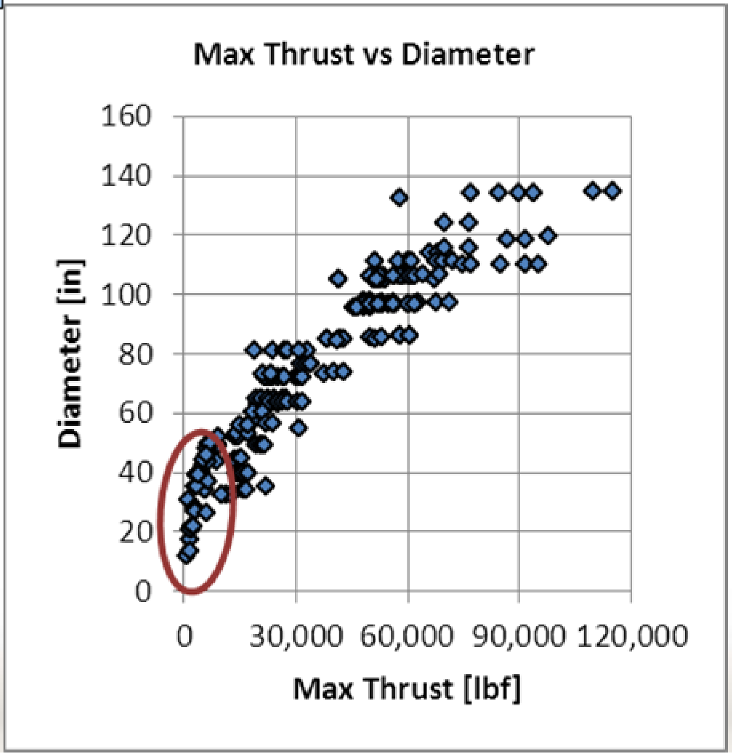


It's all about "Thrust" (con't)

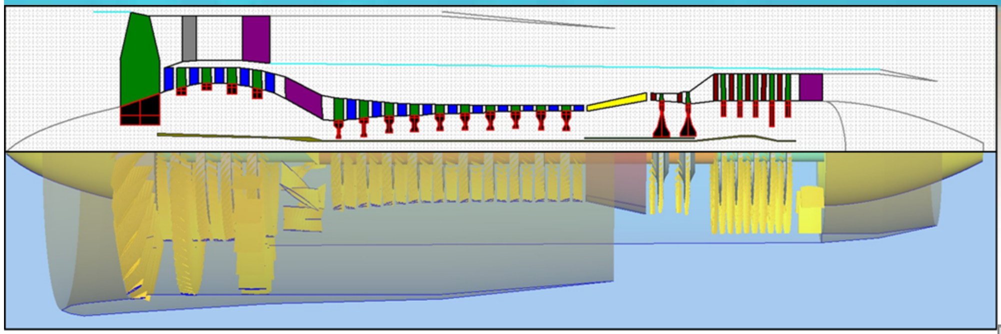


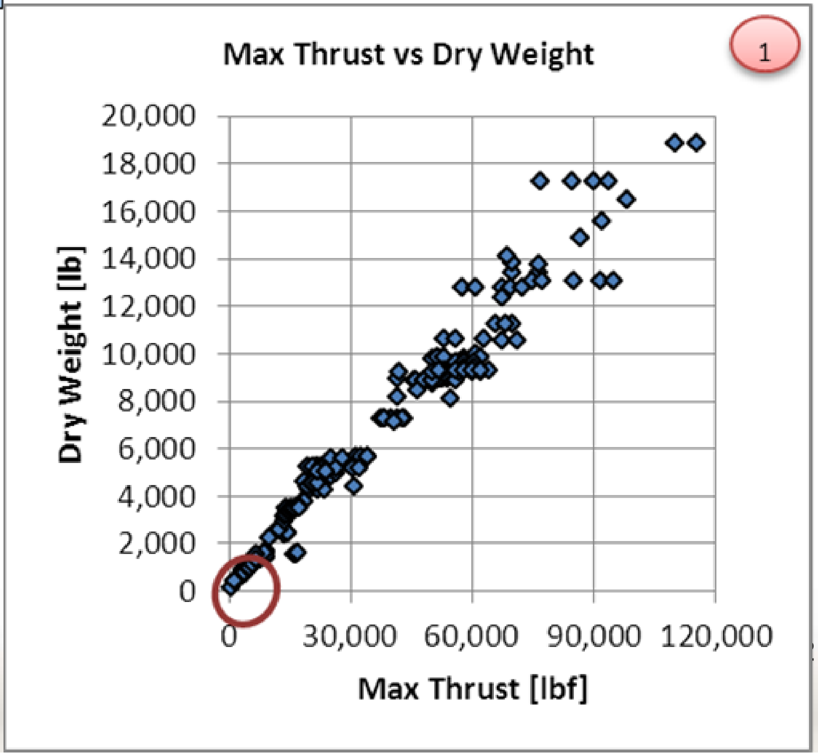
Fan diameter

Size
Weight



It's all about "Thrust" (con't)

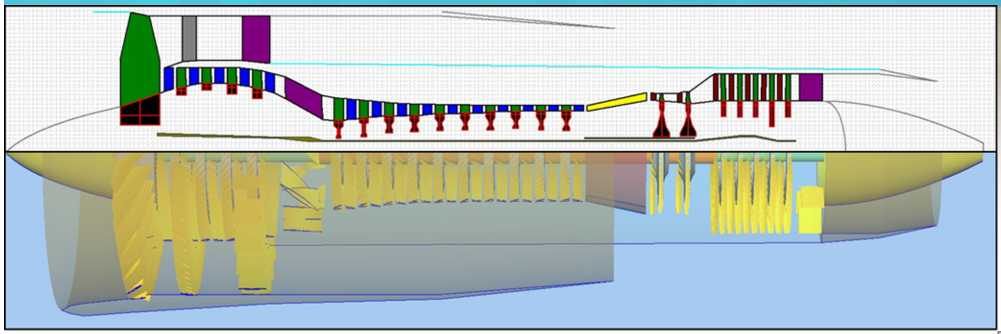


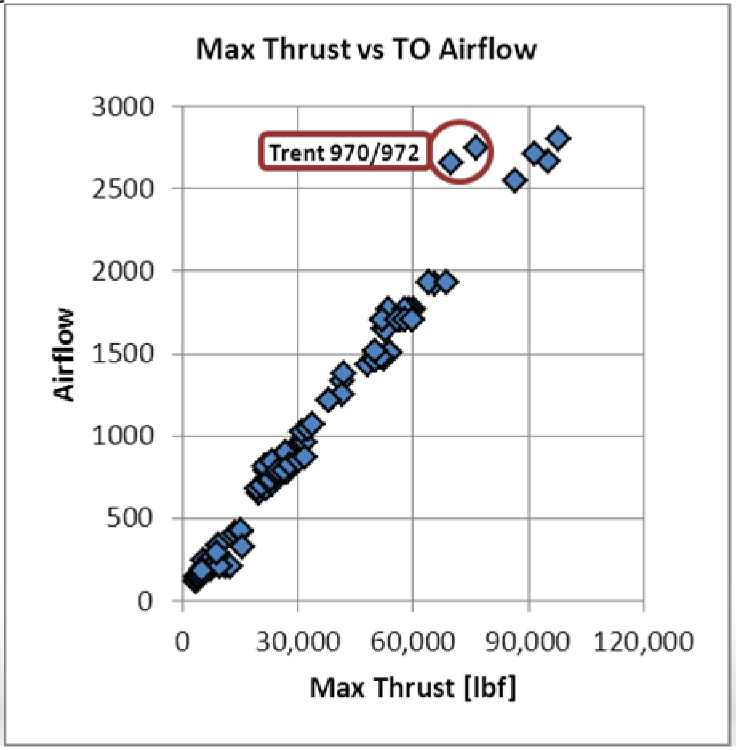


Weight

Time for a diet
and
Stay on target

It’s all about “Thrust” (con’t)

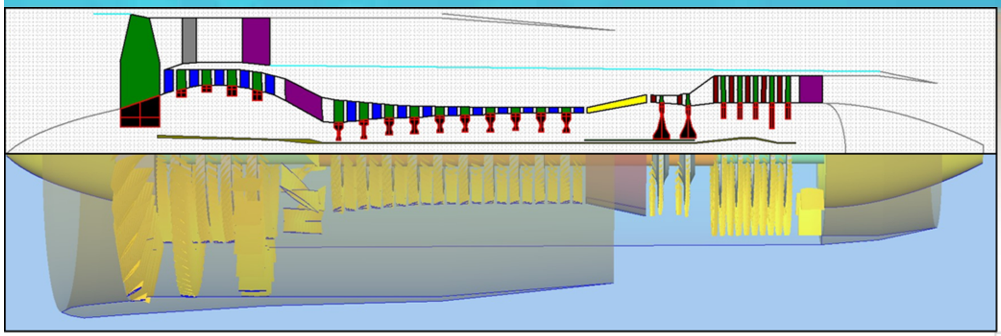


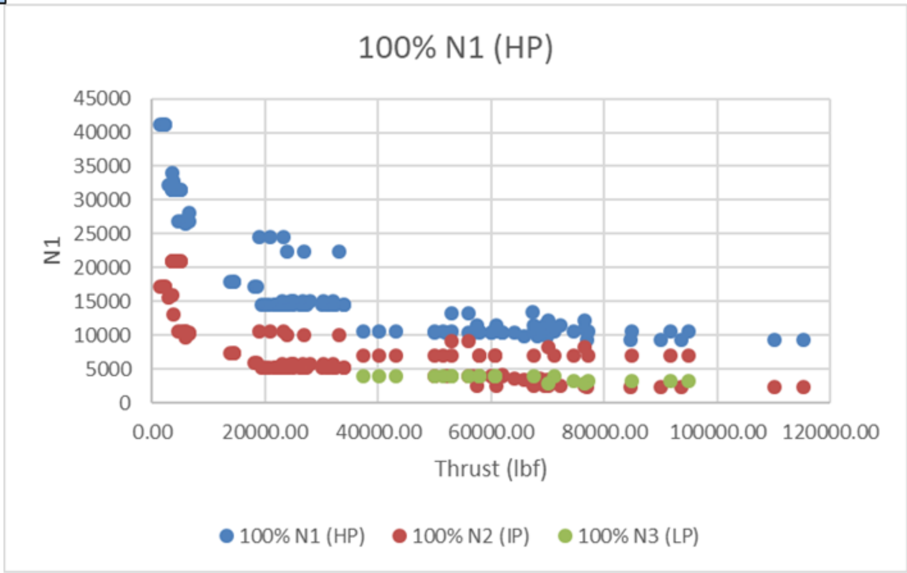


Air flow

The driving fluid Performance

It's all about "Thrust" (con't)

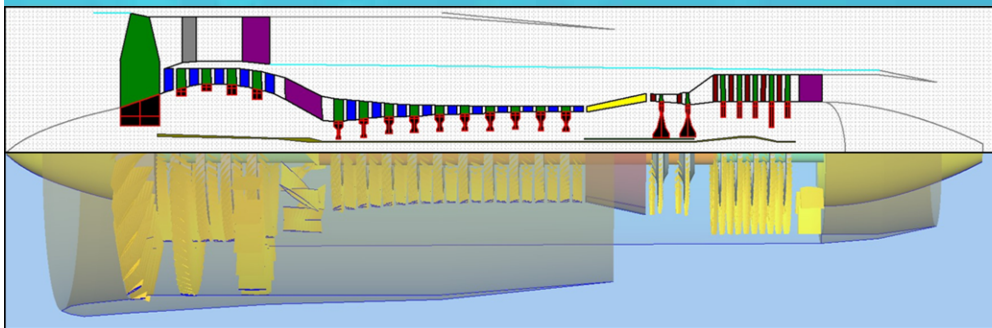




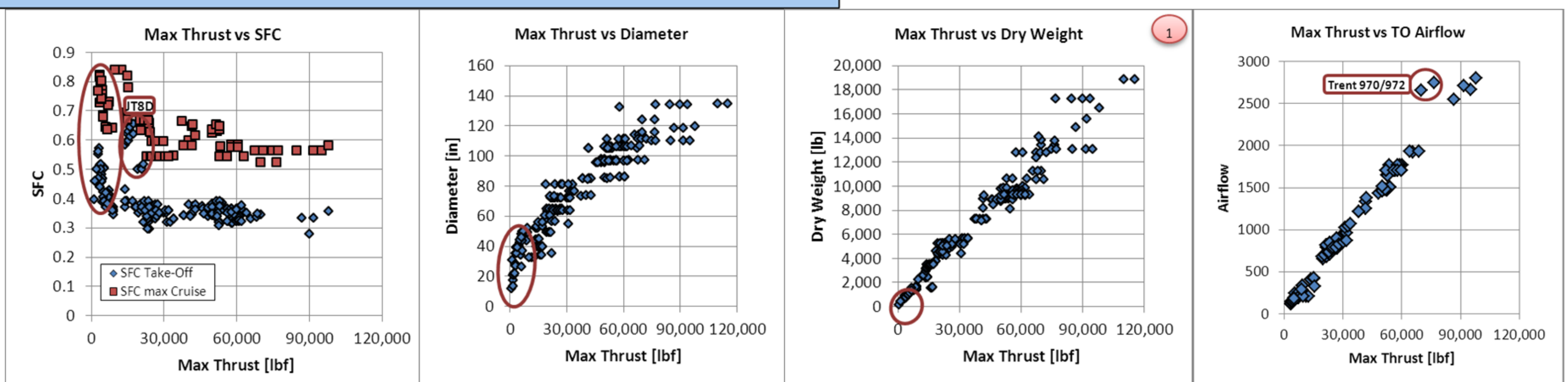
RPM

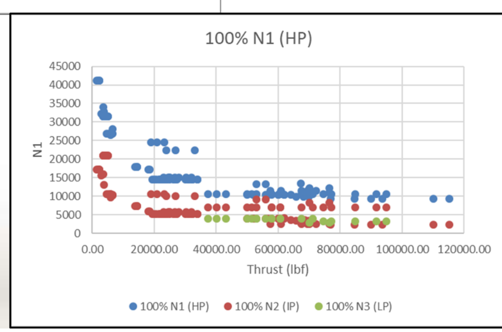
Stress
Material selection
Performance
Cost

It's all about "Thrust" (con't)



Gas turbine preliminary sizing limit & trade-off curves





The basic cross sections

CHOOSING THE ENGINE CONFIGURATION

Choosing a configuration

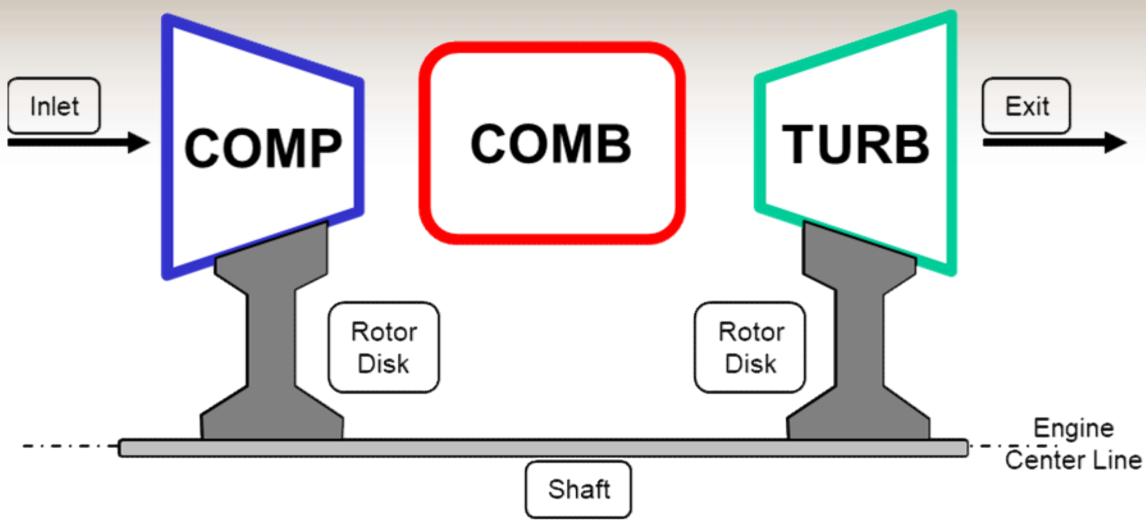
Three ingredients are required

1) a knowledge of different engine configurations

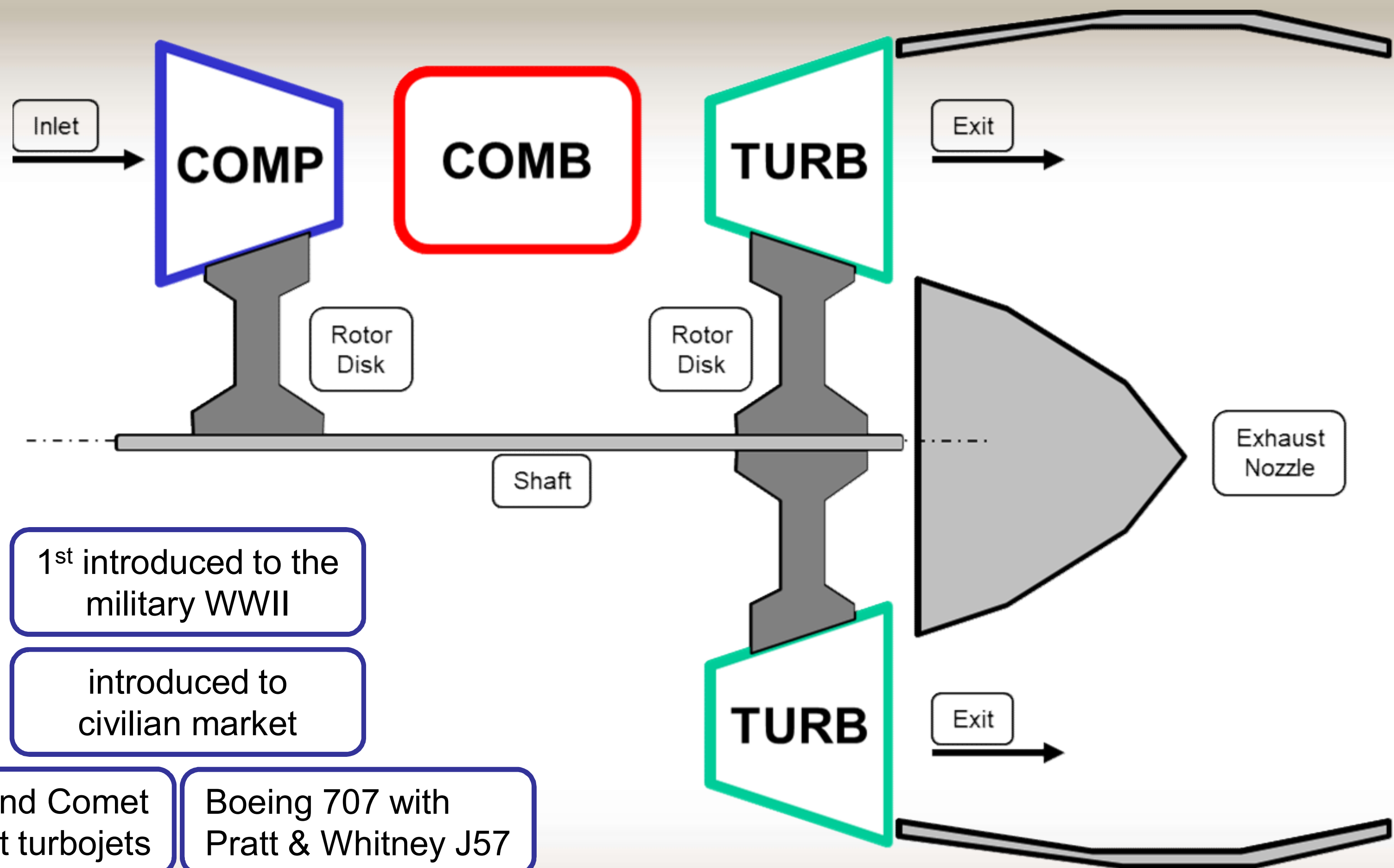
2) a historical background of existing engines

3) lots and lots of simulation models

The "core"


Inlet
COMP
COMB
TURB
Exit
Rotor
Disk
Rotor
Disk
Engine
Center Line
Shaft

The "Grandpa to all"



1st introduced to the military WWII

introduced to civilian market

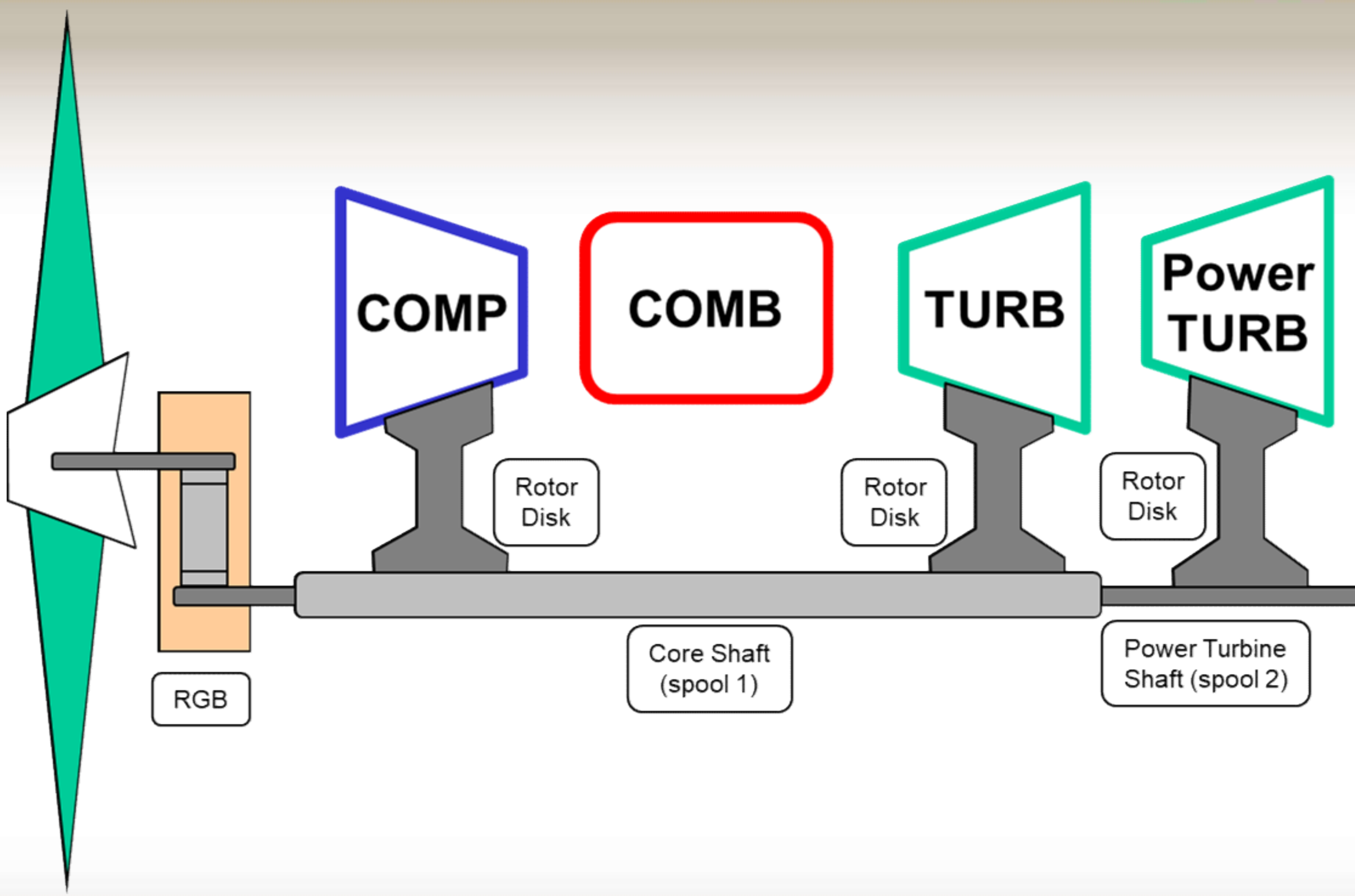
de Havilland Comet with Ghost turbojets

1949 / 1952

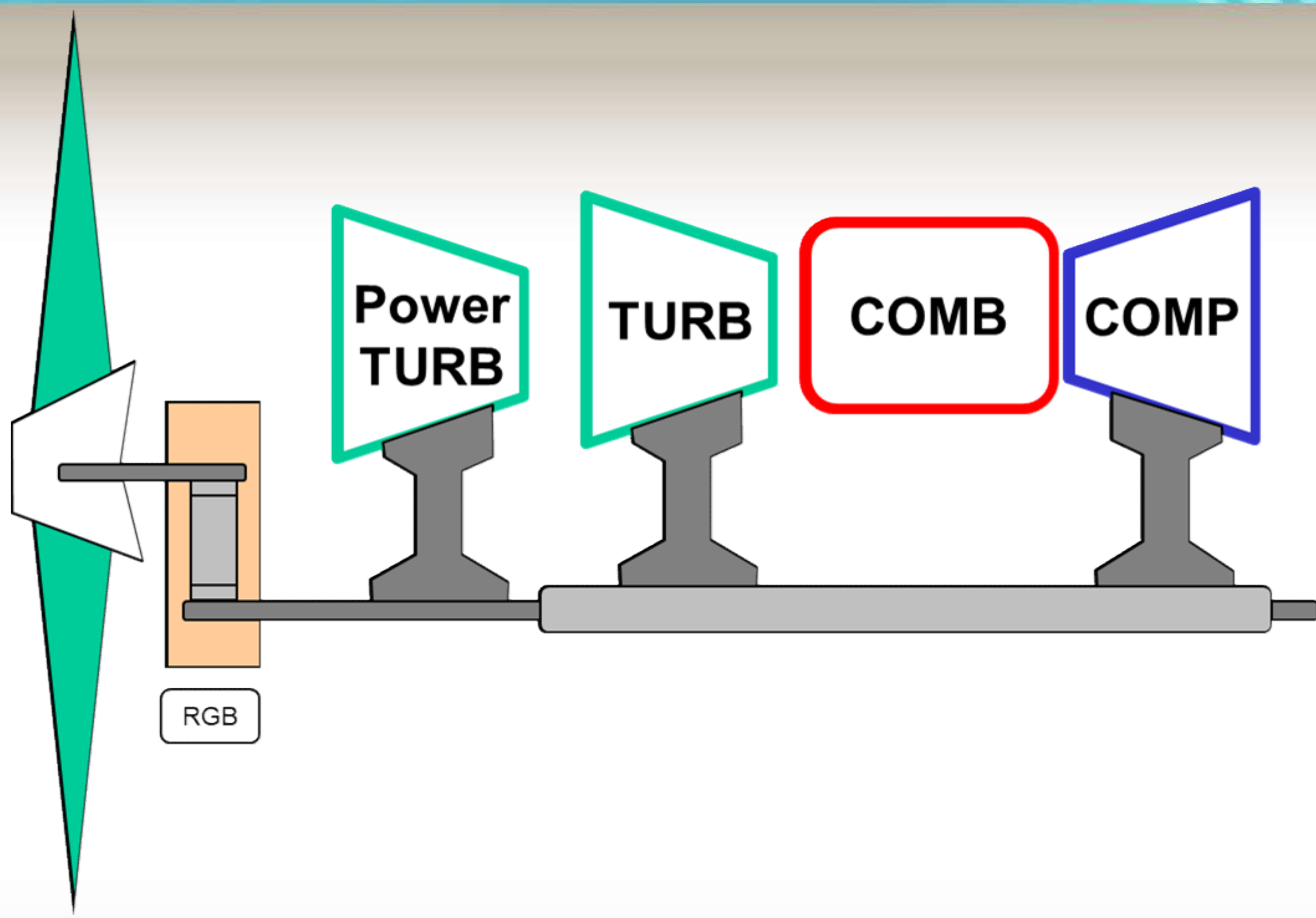
Boeing 707 with Pratt & Whitney J57

1957 / 1958

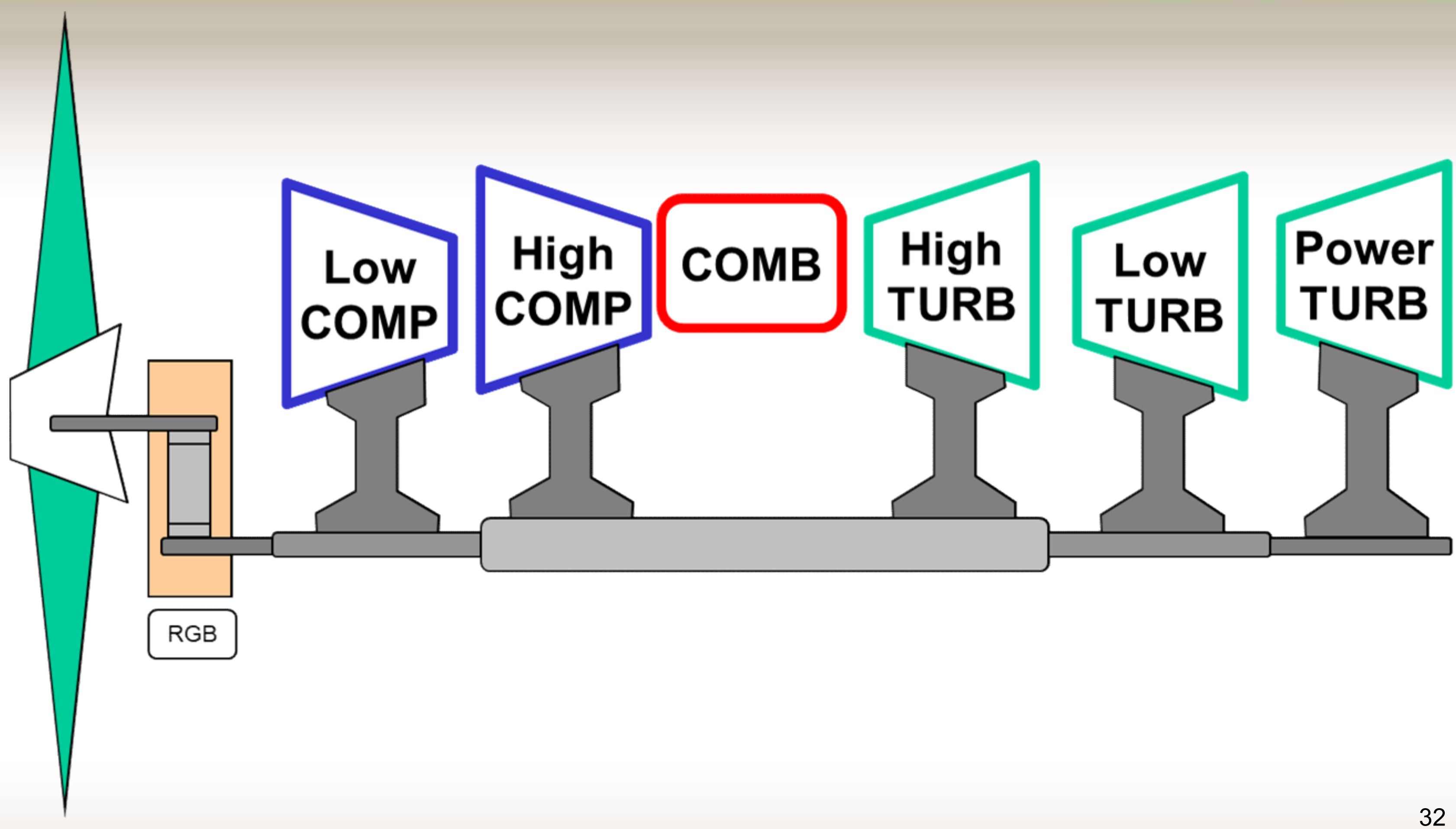
2 Spool Turbo-Prop



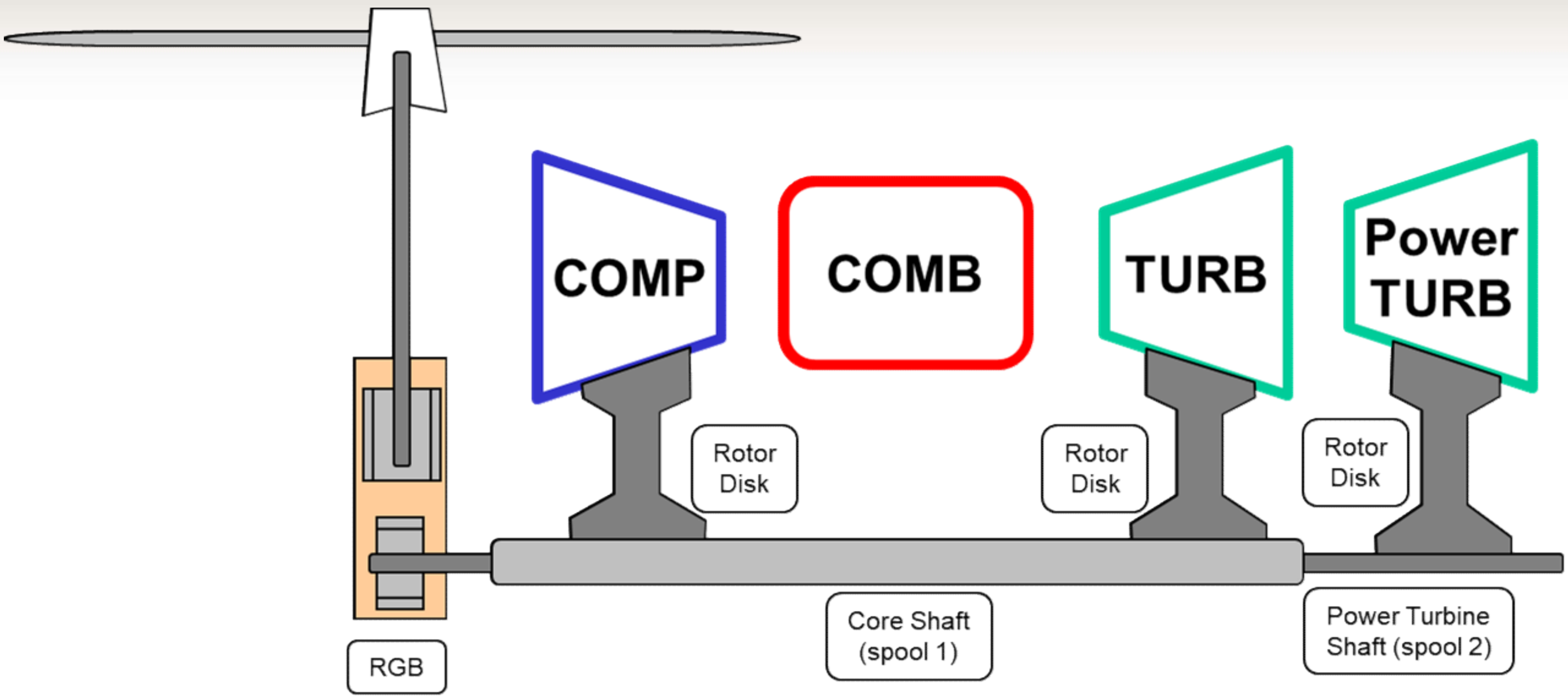
2 Spool Turbo-Prop reversed RGB



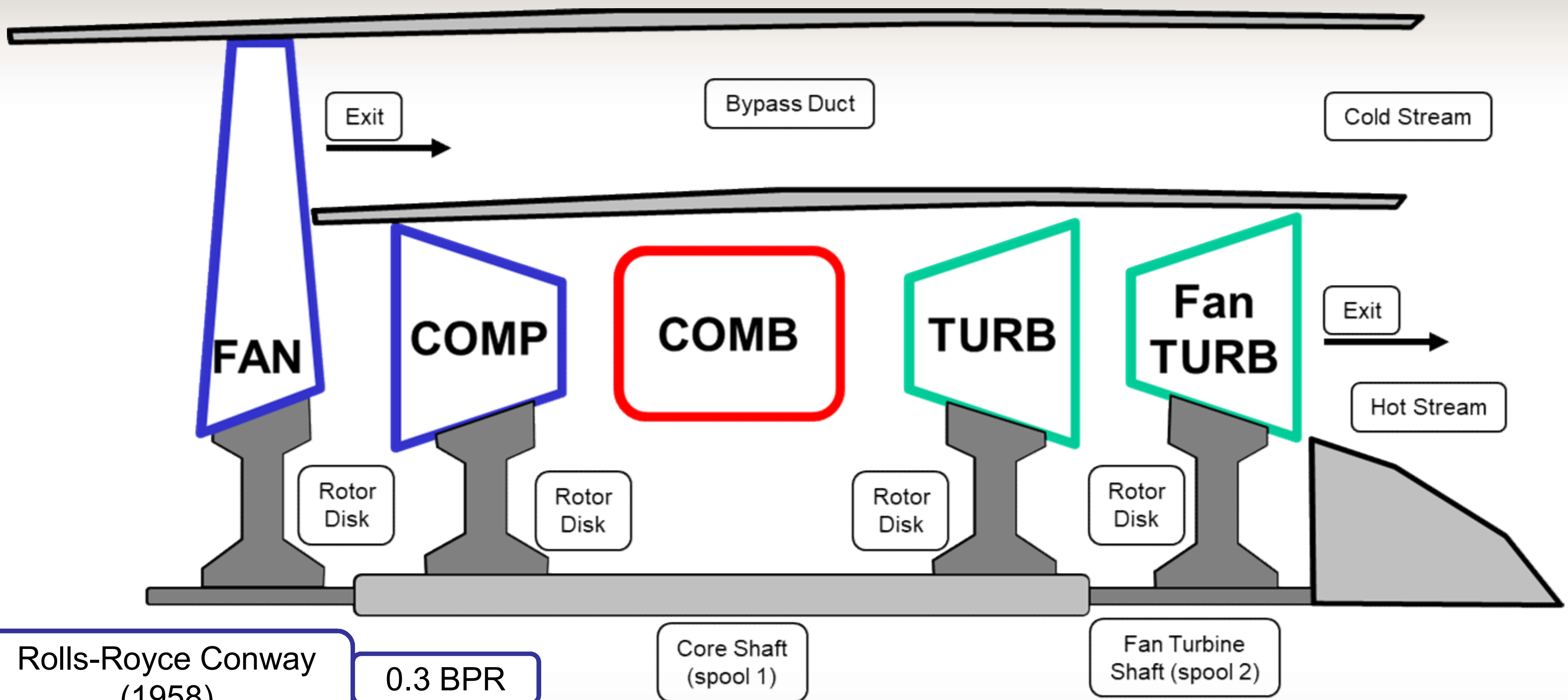
3 Spool Turbo-Prop



2 Spool Turbo-Shaft

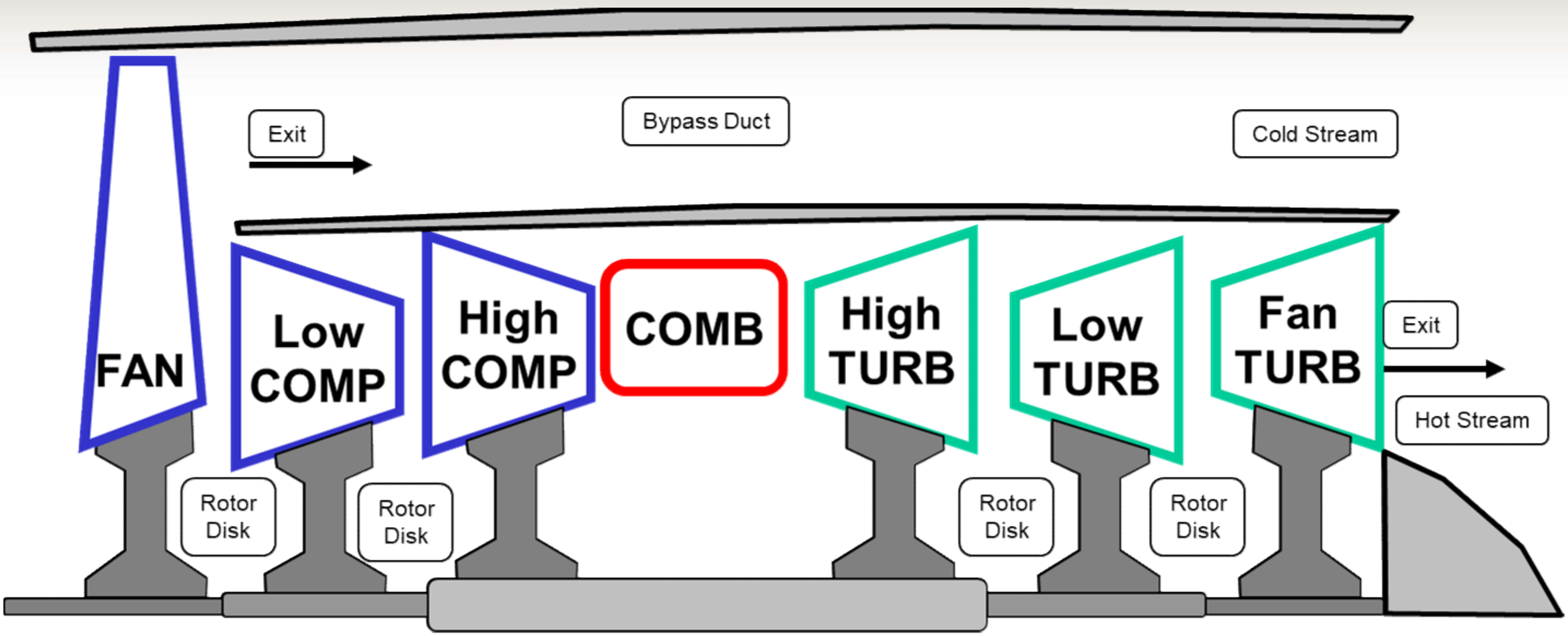


2 Spool Turbo-Fan

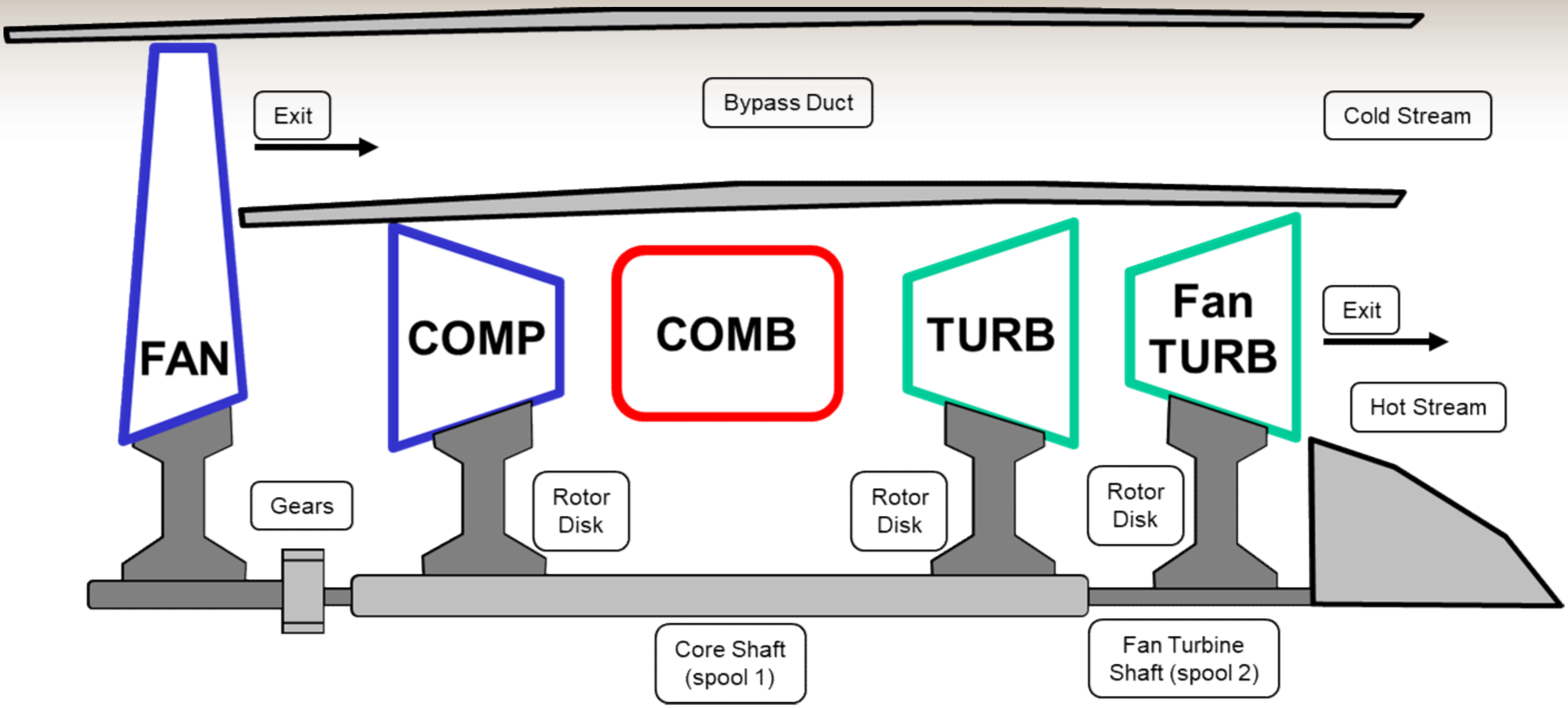


Rolls-Royce Conway (1958)	0.3 BPR
Pratt & Whitney JT3D (1959)	1.42 BPR

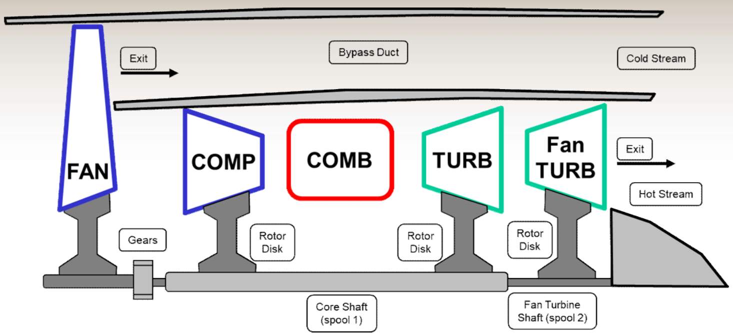
3 Spool Turbo fan



2 Spool Geared Turbo-Fan



2 Spool Geared Turbo-Fan

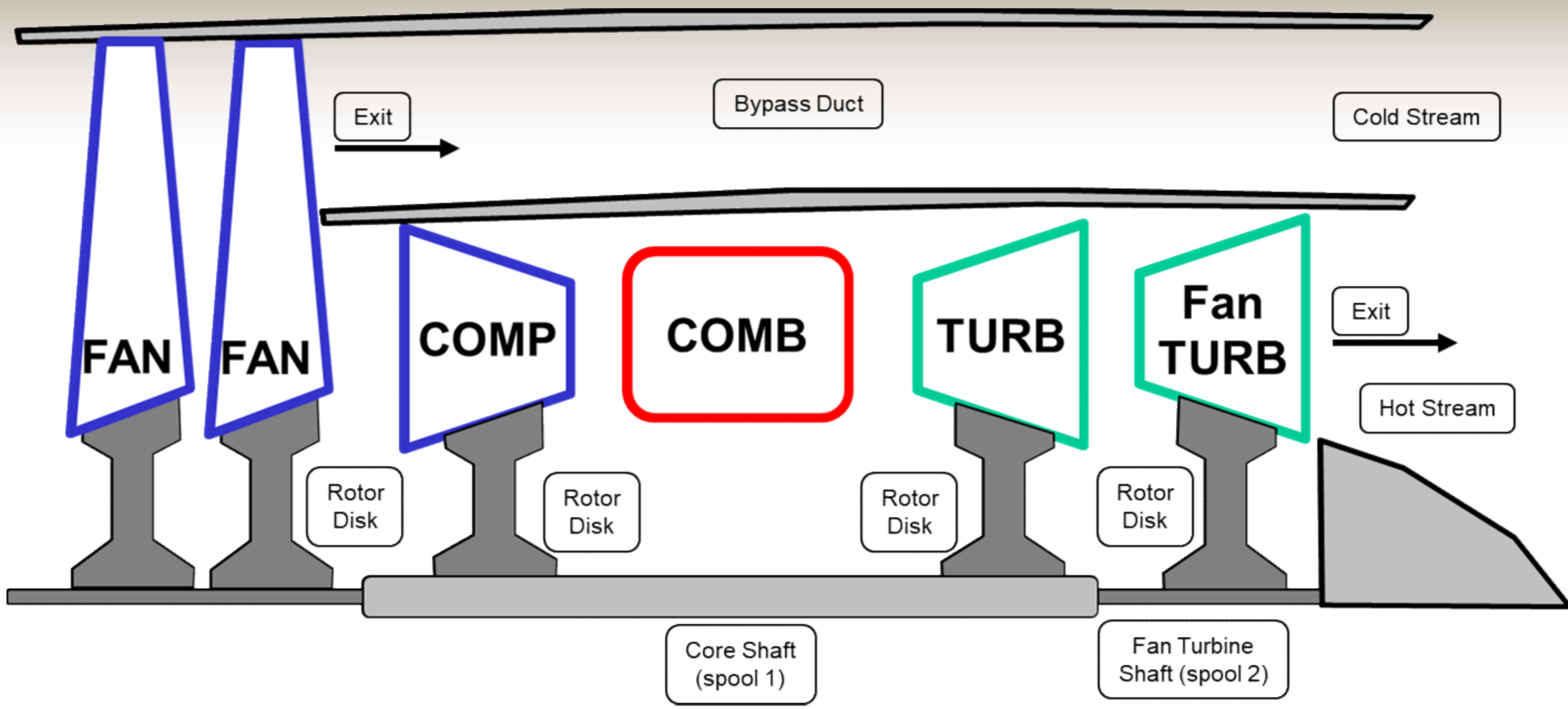


COMPANY	ENGINE	TIMEFRAME	COMMENT
Honeywell	TFE731	1972	
GE	QCSEE	1974	NASA design contract
Honeywell	ALF 502/507	1980	
IAE	SuperFan	1986	Engineering study only
Pratt & Whitney	PW1000G	2012	
United Engine Corporation	PD-30	TBD	
Rolls-Royce	UltraFan	TBD	

Is the UltraFan a reincarnation of the SuperFan? … I wonder …

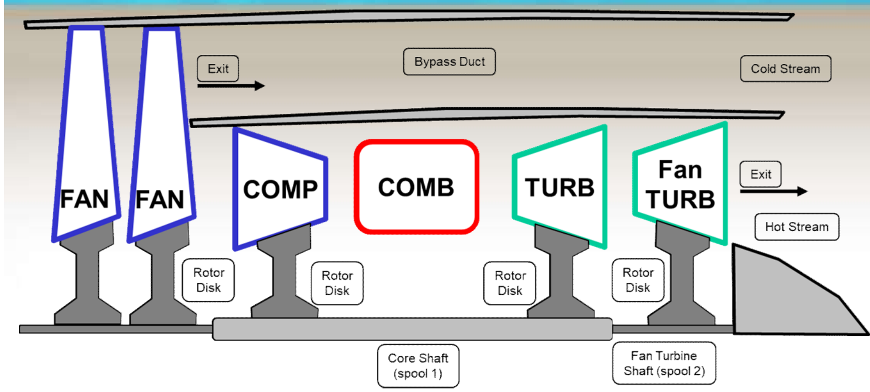
2 Spool Double-Fan Turbo-Fan

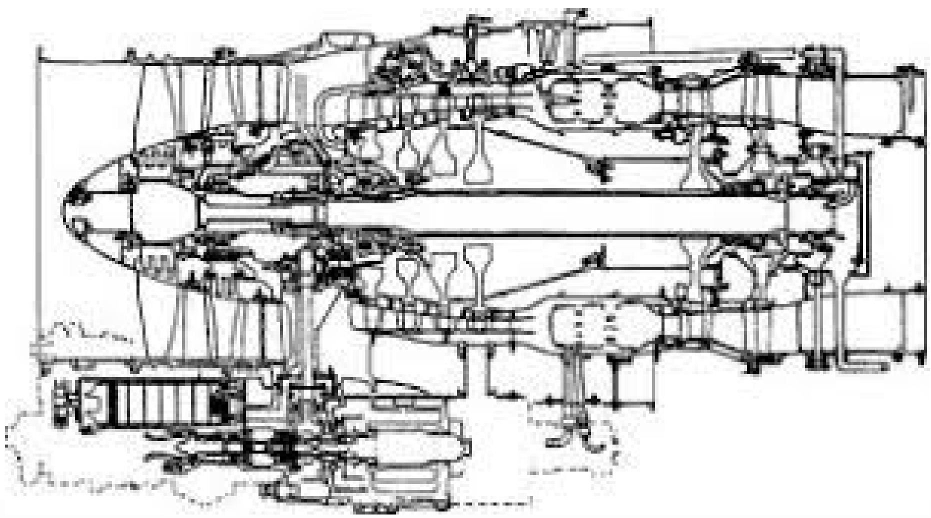
NEW in 2018
By GE



2 Spool Double-Fan Turbo-Fan

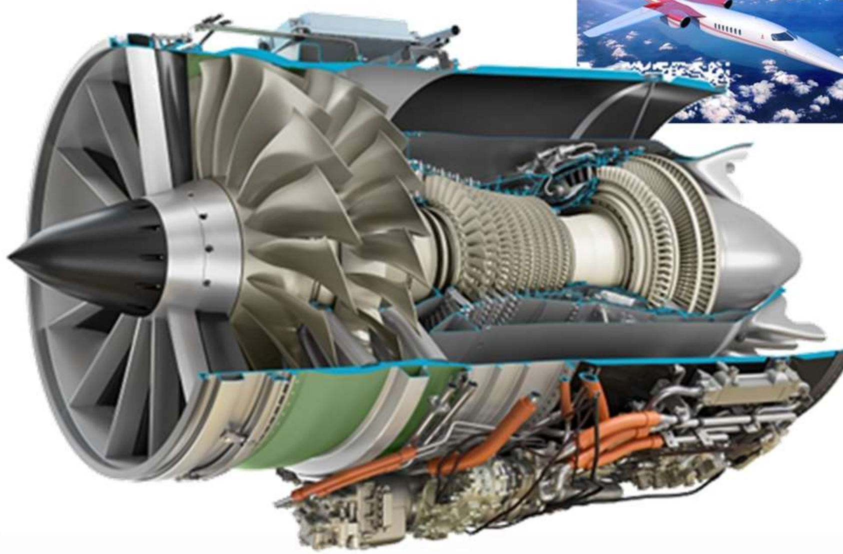
NEW in 2018 By GE





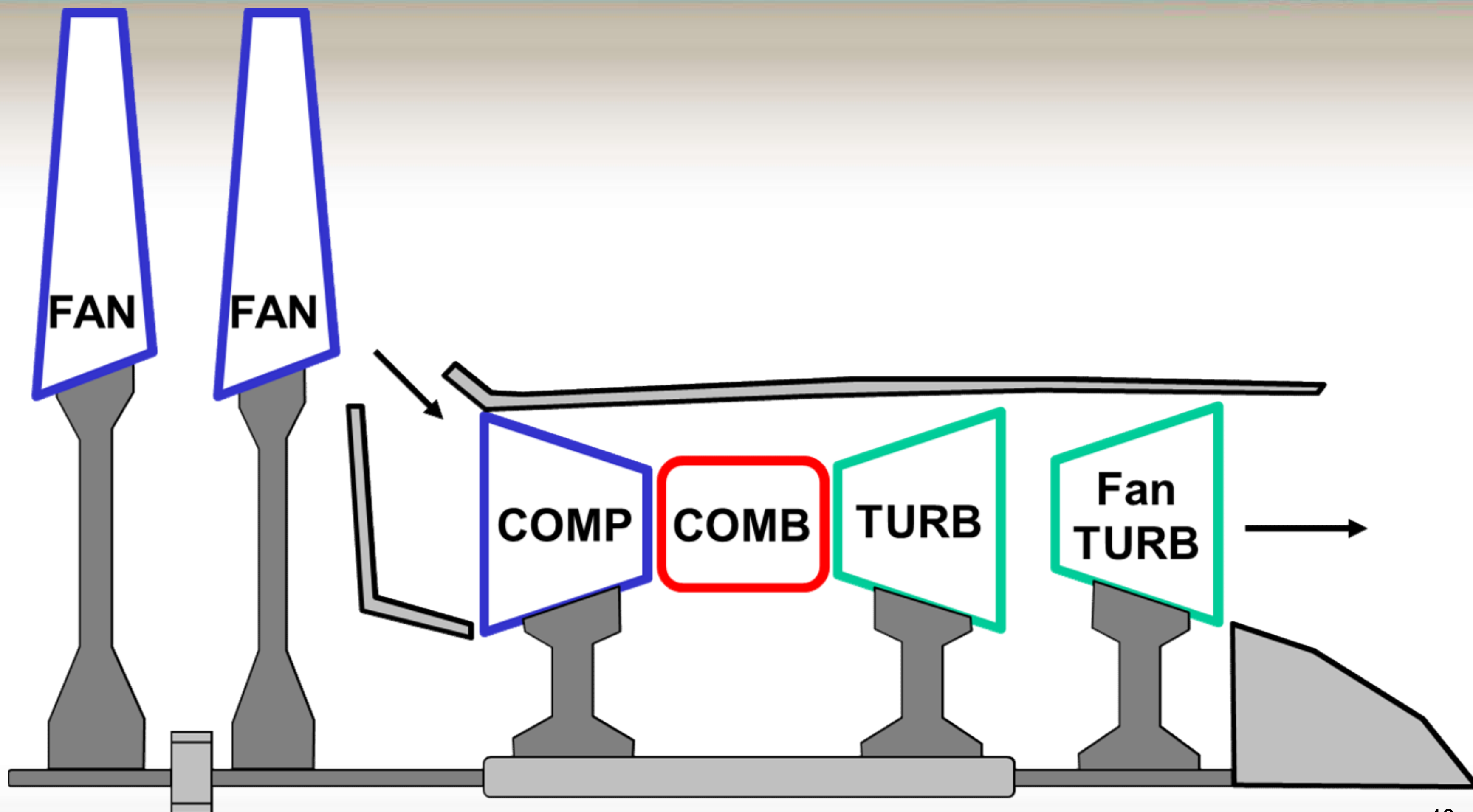
SAFRAN Larzac 04 (military)

1969, 1982, 1984



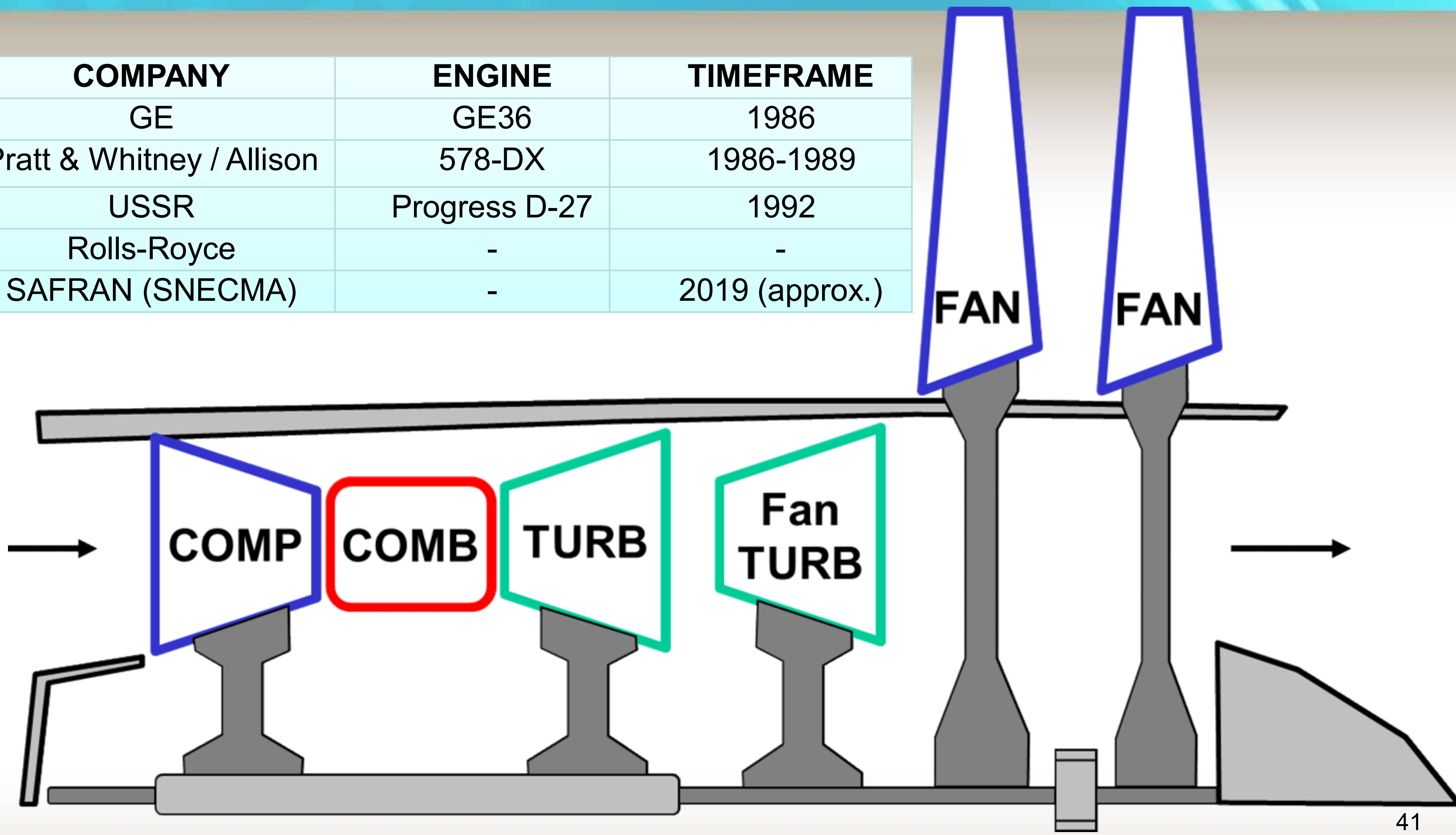
GE Affinity (Civilian supersonic)

Open Rotor Forward Fan



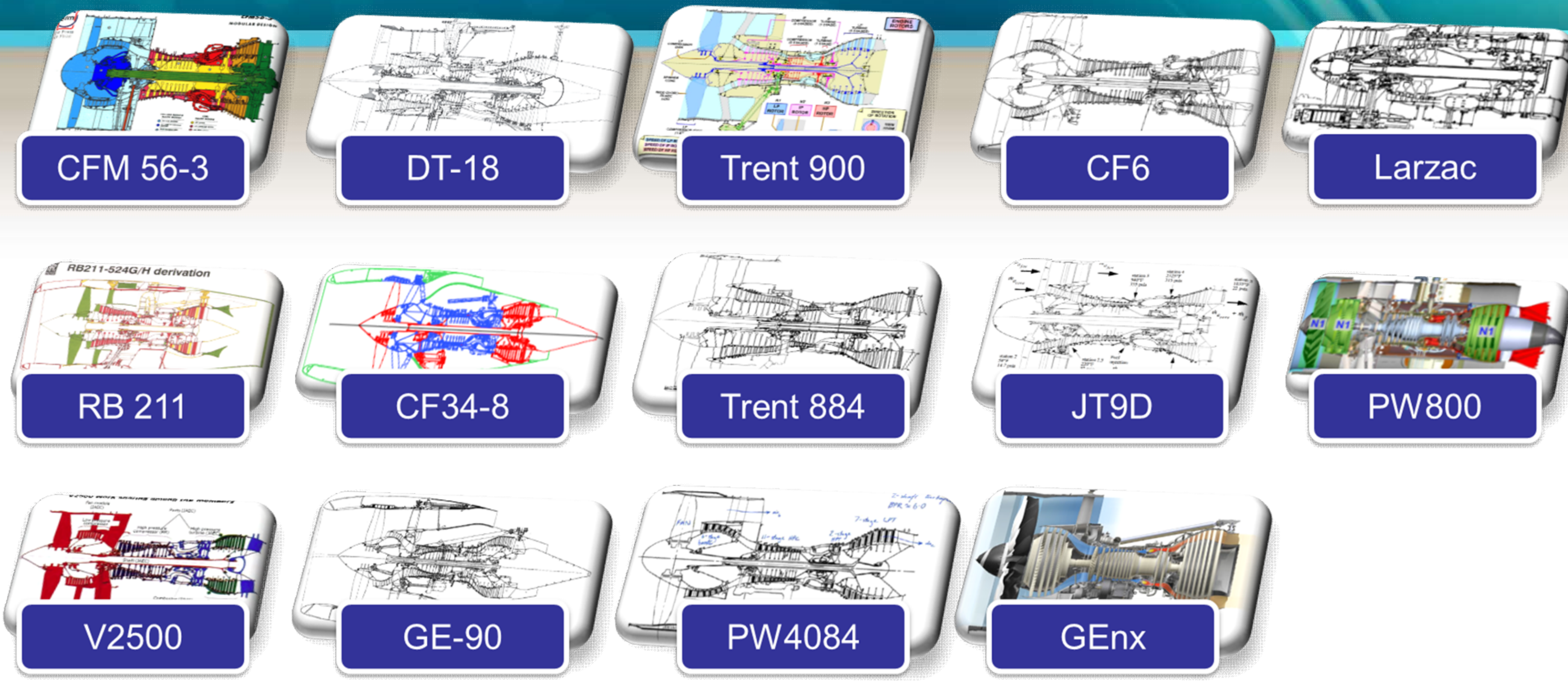
Open Rotor Rear Fan

COMPANY	ENGINE	TIMEFRAME
GE	GE36	1986
Pratt & Whitney / Allison	578-DX	1986-1989
USSR	Progress D-27	1992
Rolls-Royce	-	-
SAFRAN (SNECMA)	-	2019 (approx.)



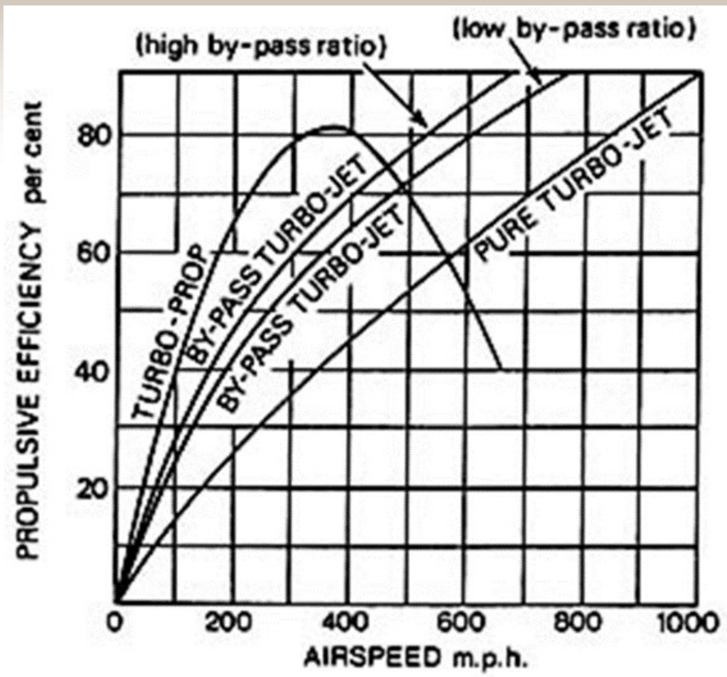
How do we choose which configuration?

Database of engines



Successful production engine data	"biased" clean sheets and derivatives	Model & simulation validation	Incorporation of new or improved technologies

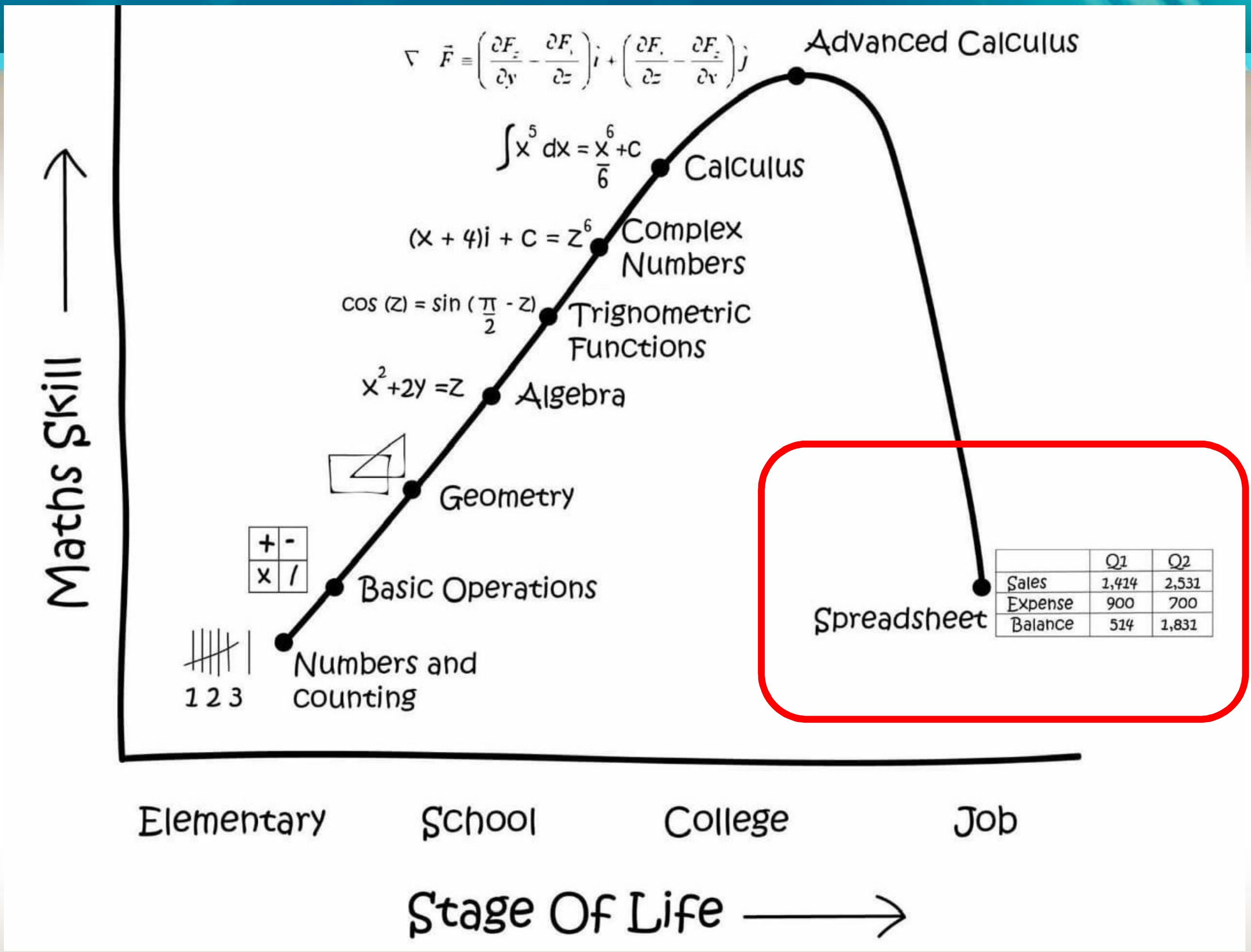
How do we choose which configuration?



- $f(x)$
- EI
- NI
- Mgt
- Next slide

EI: Emotional Intelligence
NI: Natural Intelligence

And lots of sophisticated spreadsheets

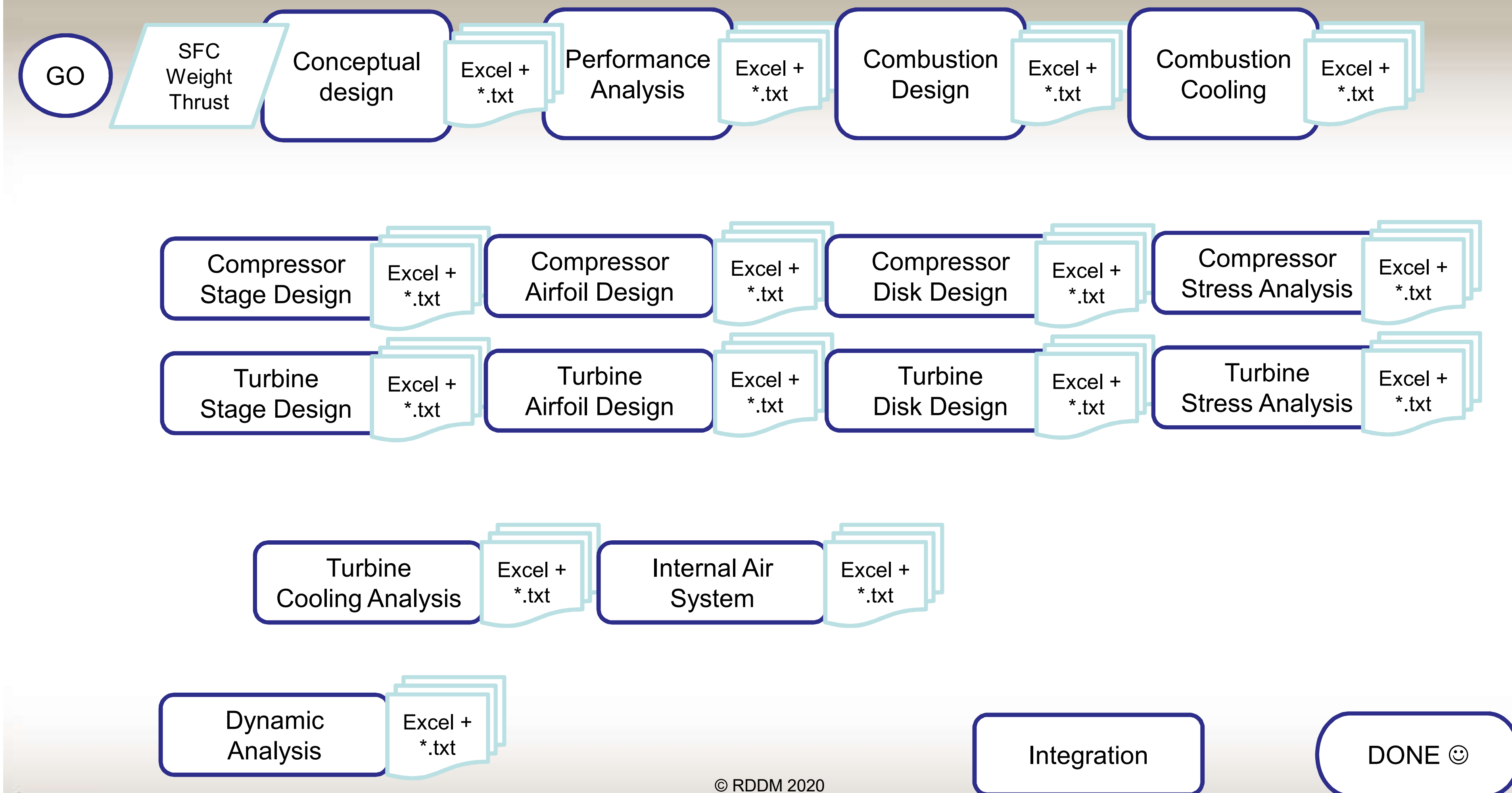


"It is common sense to take a method and try it. If it fails, admit it frankly and try another. But above all, try something."- **Franklin D. Roosevelt**

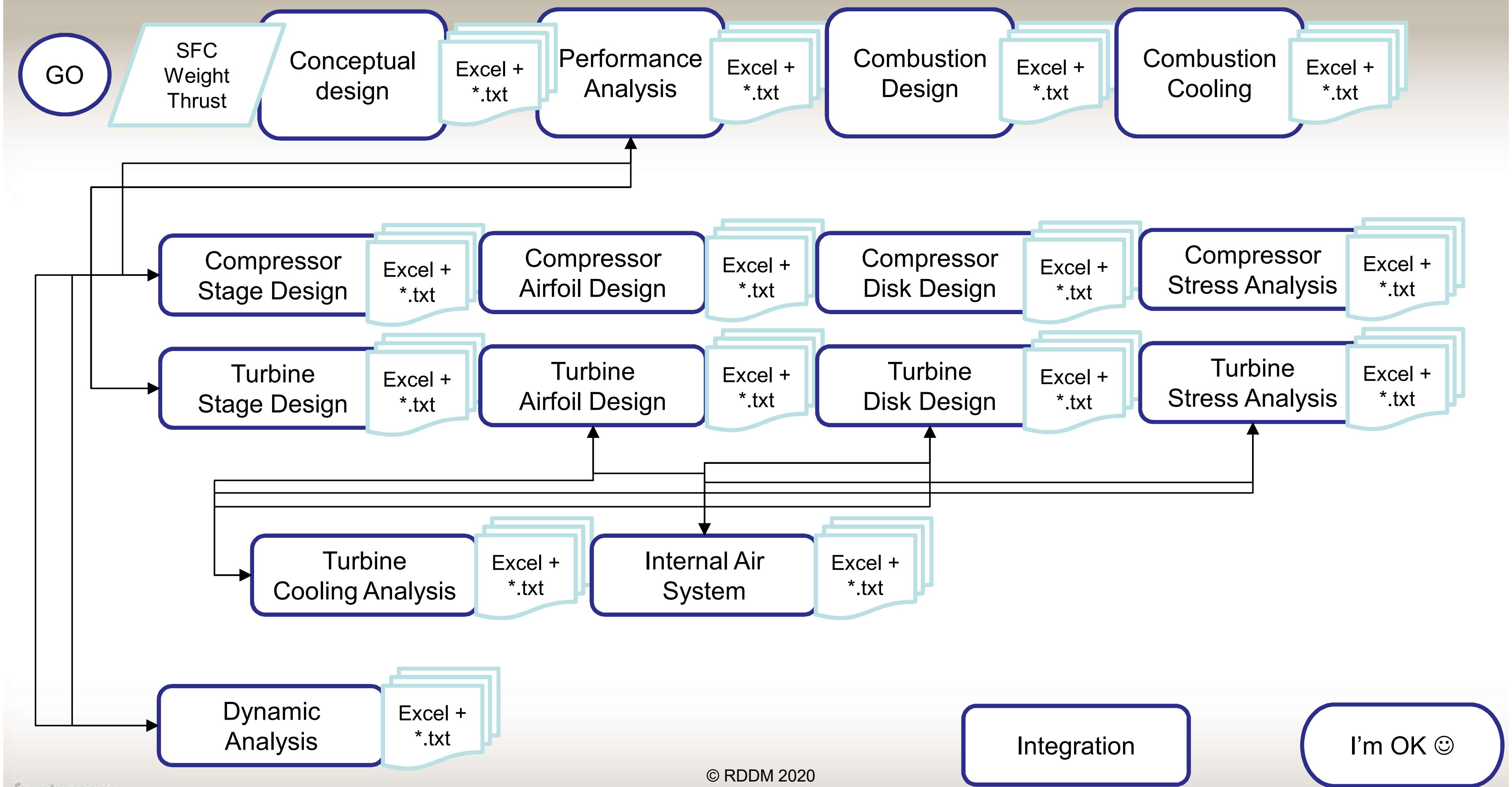
The (disastrous) design process

MULTI-DISCIPLINARY (INTEGRATED) DESIGN (& OPTIMIZATION) SYSTEM

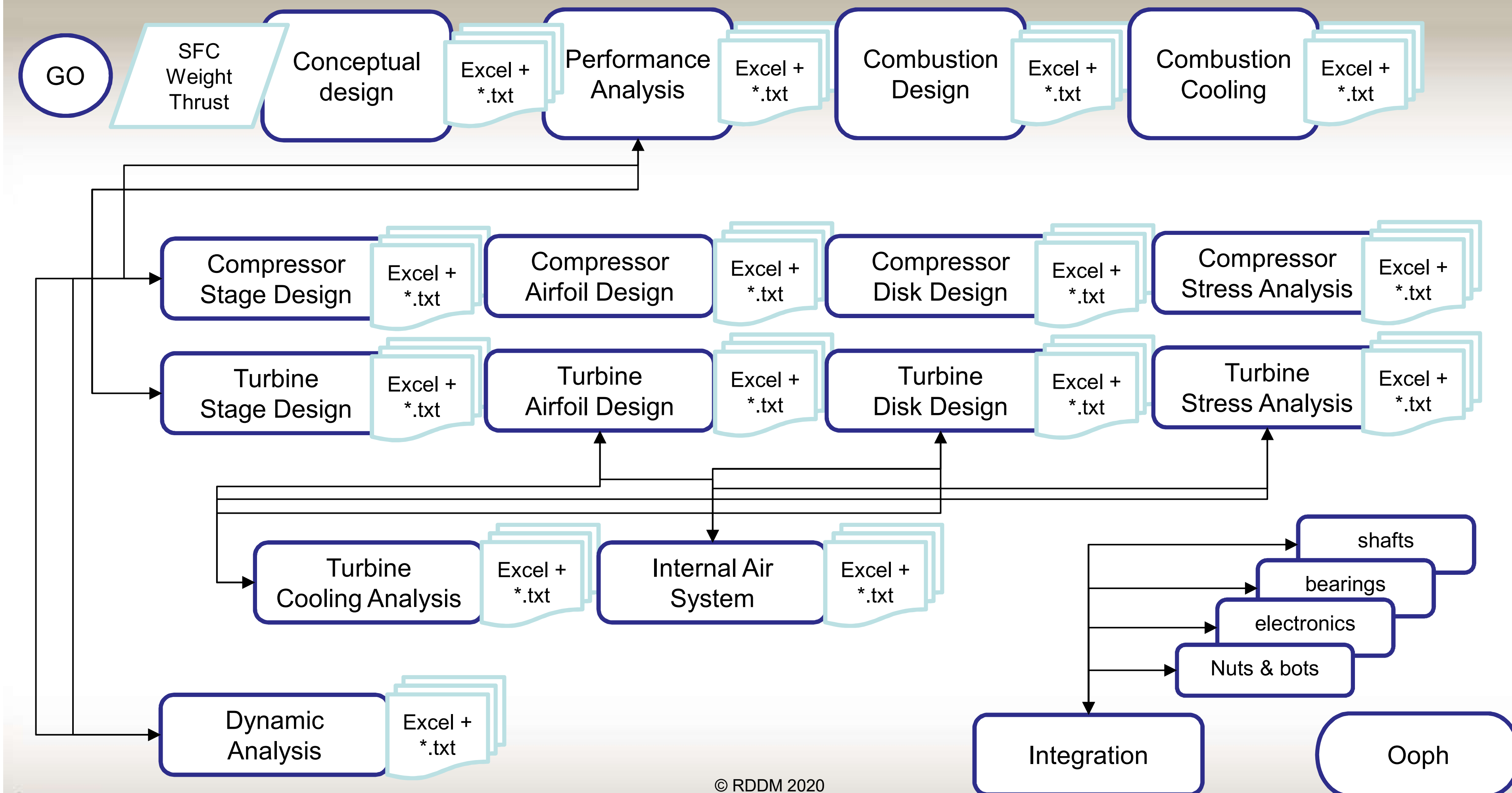
A <u>simplified</u> value stream



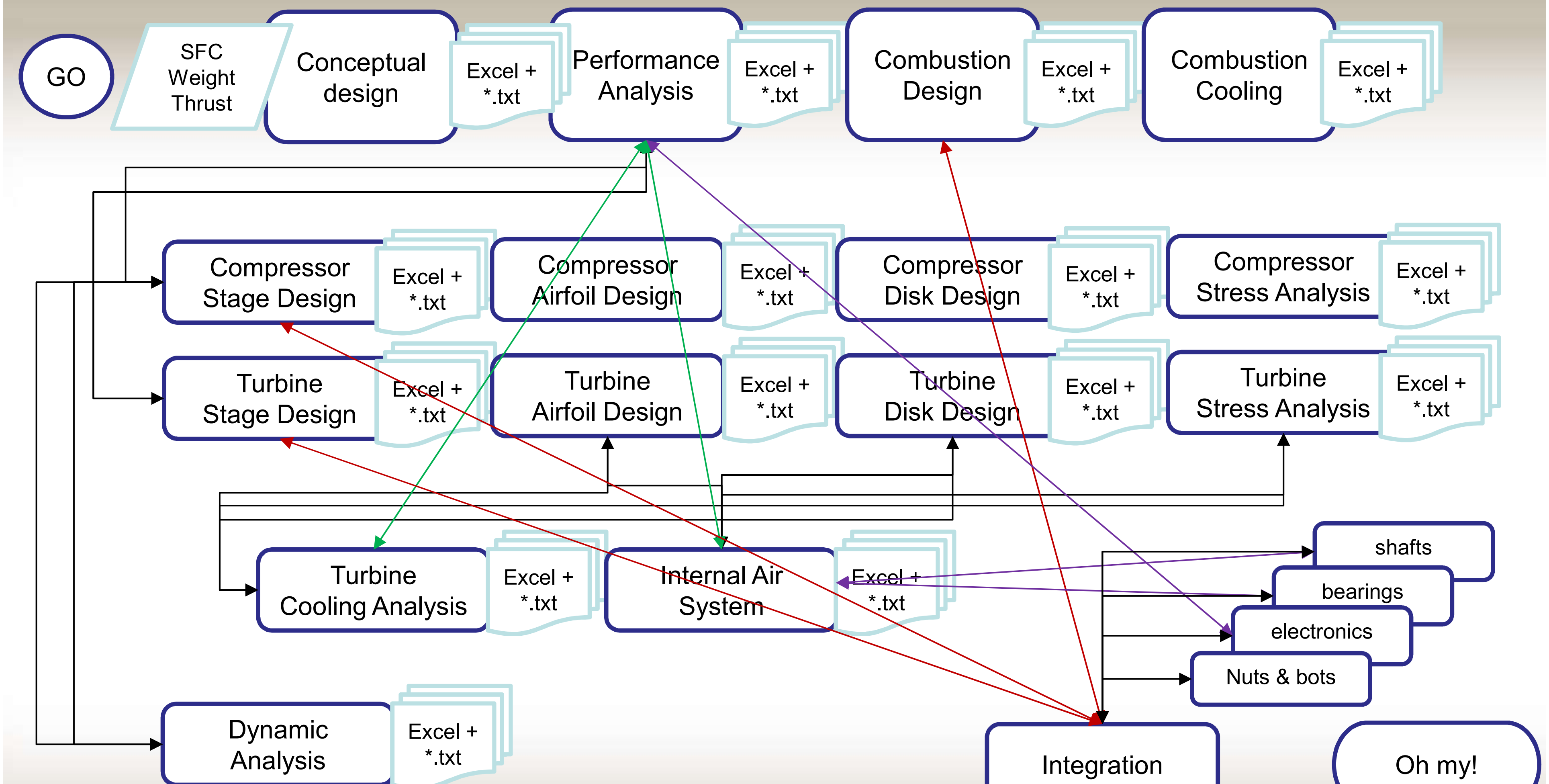
An iterative value stream

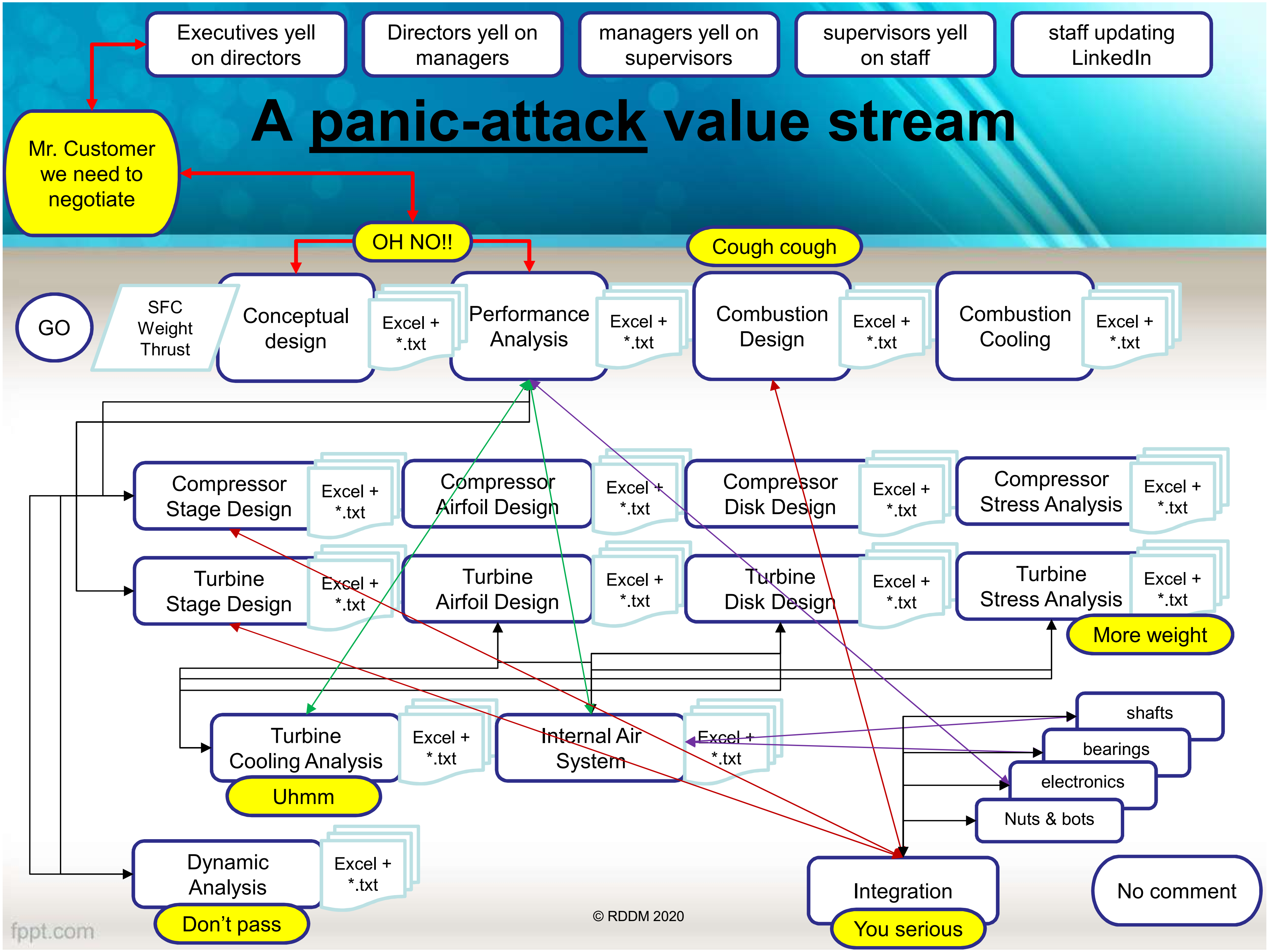


A not so bad value stream



A stressful value stream




A panic-attack value stream
Executives yell on directors
Directors yell on managers
managers yell on supervisors
supervisors yell on staff
staff updating LinkedIn
Mr. Customer we need to negotiate
OH NO!!
Cough cough
GO
SFC Weight Thrust
Conceptual design
Excel + *.txt
Performance Analysis
Excel + *.txt
Combustion Design
Excel + *.txt
Combustion Cooling
Excel + *.txt
Compressor Stage Design
Excel + *.txt
Compressor Airfoil Design
Excel + *.txt
Compressor Disk Design
Excel + *.txt
Compressor Stress Analysis
Excel + *.txt
Turbine Stage Design
Excel + *.txt
Turbine Airfoil Design
Excel + *.txt
Turbine Disk Design
Excel + *.txt
Turbine Stress Analysis
Excel + *.txt
More weight
Turbine Cooling Analysis
Excel + *.txt
Uhmm
Internal Air System
Excel + *.txt
shafts
bearings
electronics
Nuts & bots
Dynamic Analysis
Excel + *.txt
Don't pass
Integration
You serious
No comment
© RDDM 2020
fppt.com

And remember …

The most dangerous phrase in the language is,

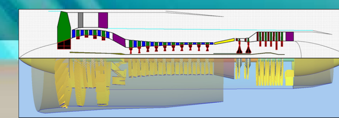
"We've always done it this way."

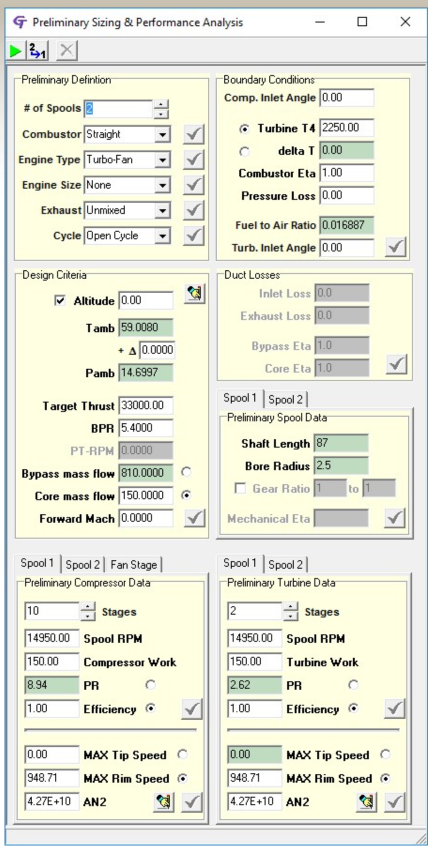
- Rear Admiral Grace Murray Hopper

The design process

WHAT EACH DISCIPLINE DOES

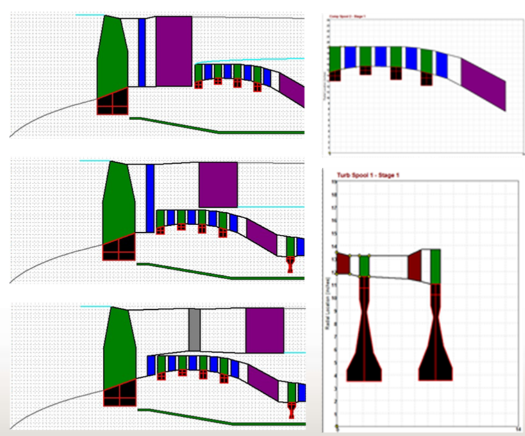
Conceptual Design & Performance



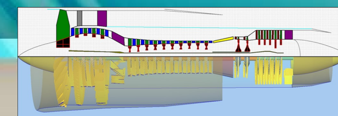


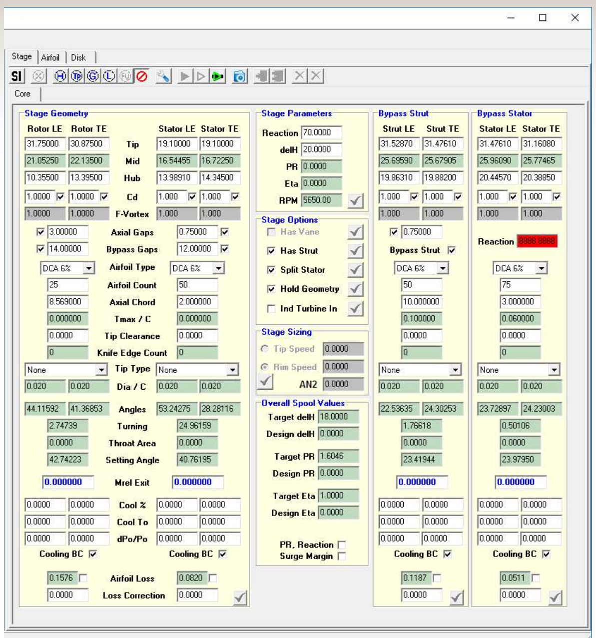
The engineer:

- Creates different gas turbine configurations
- Suggests stage counts based on past experience or optimization
- Develops a simplified design-point performance condition
- Executes a simplified performance analysis
- Executes complex steady- and transient- performance analysis
- Repatriates the detailed design values to the design-point and off-design performance condition for iterative convergence



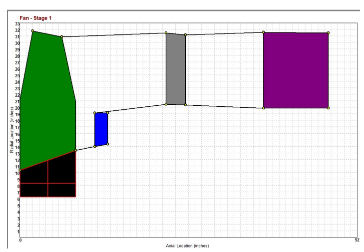
The compressor and turbine aerodynamicist

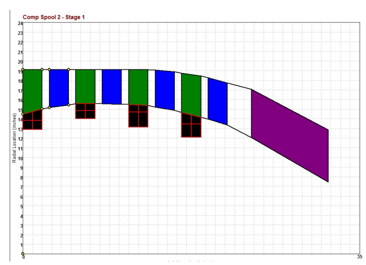


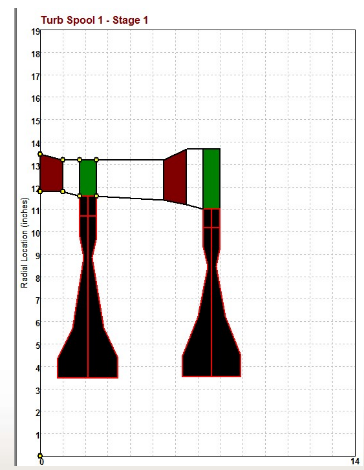


The engineer:

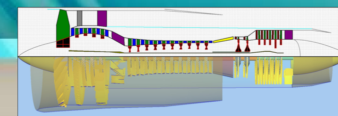
- Executes the 1D design-point and off-design mean-line
- Designs and analyzes:
  - Fan stage(s)
  - Axial and Centrifugal Compressor stage(s)
  - Axial Turbine stage(s)
    - Cooled or Uncooled

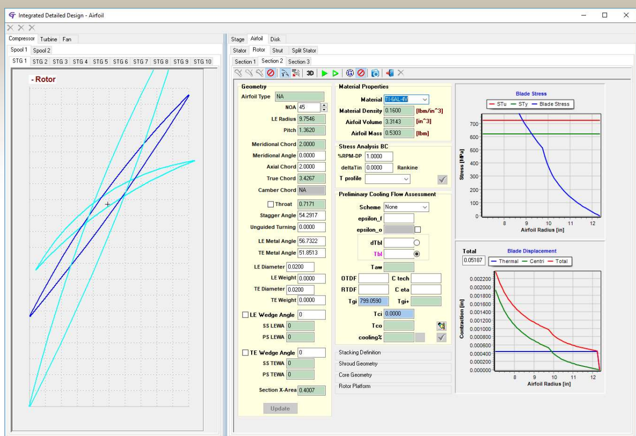


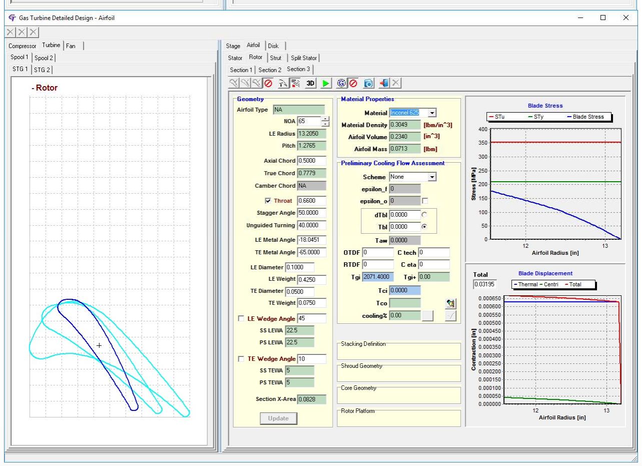




Aerodynamics, cooling, and stress







The engineer designs the airfoils for:

- Fan stage(s)
- Compressor (axial and/or centrifugal) stages
- Axial Turbine stages

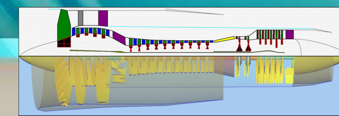
The engineer also:

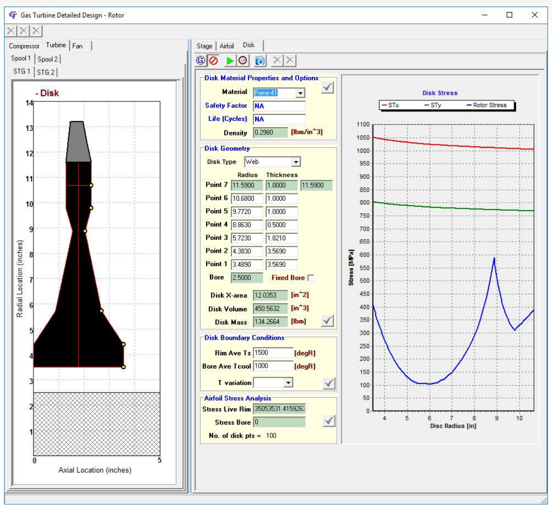
- Executes simplified and complex stress analysis
- Executes preliminary and detailed cooling flow design and analysis

Airfoils include

- Stator, Rotor, Strut, and Bypass Stator

Disk design and stress

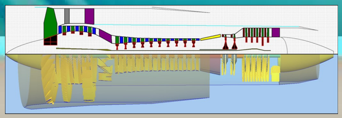


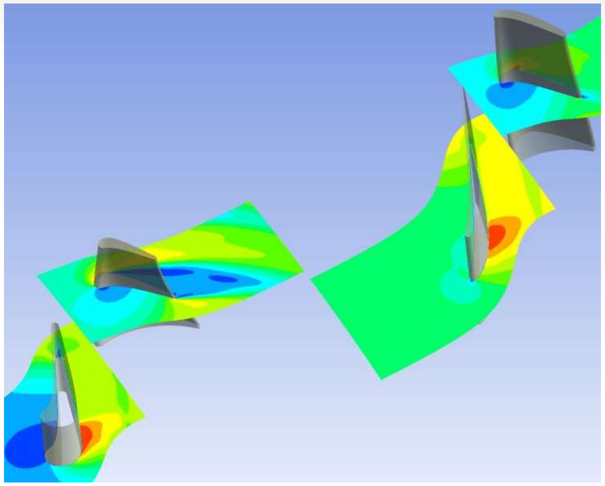


The engineer:

- Creates different axisymmetric disk profiles
- Executes simplified and complex stress analysis
- Executes blade fixing analysis

xD analysis



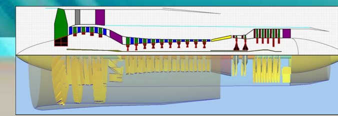


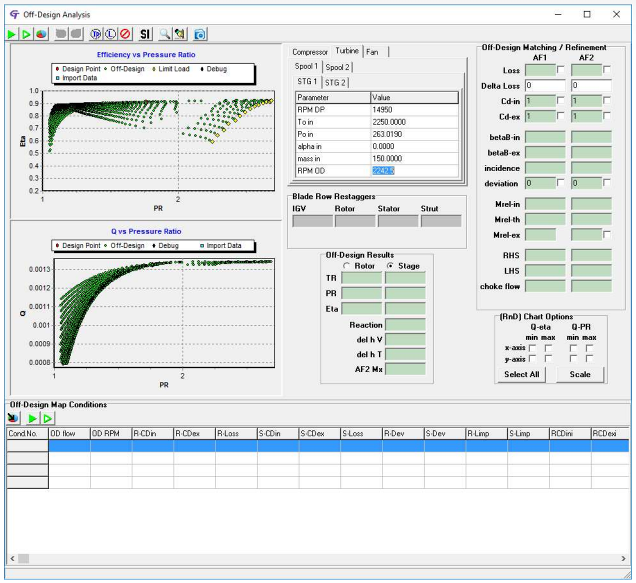
The engineer:

- Executes 2D through-flow analysis
- Executes 3D CFD
  - Steady state and transient analysis
  - (or) Time invariant and time variant
- Fine tunes the aerodynamics
- Updates mean-line and through-flow performance values based on 3D analysis

GE likes to use the term “3D aero design”

Off design behaviour

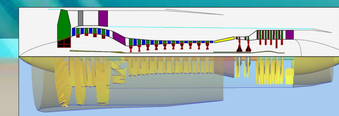


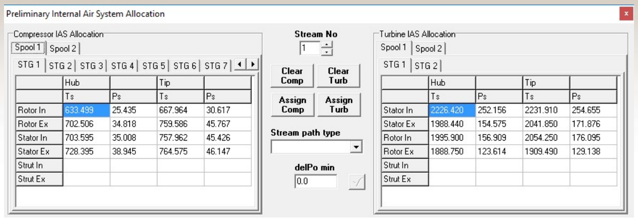


The engineer:

- Executes off-design analysis to feed Performance group
    - Compressor off-design
    - Turbine off-design
    - IAS
    - Stress
- May execute 1D, 2D, and/or 3D off-design analysis

Air system





Preliminary Internal Air System Allocation

Compressor IAS Allocation

Spool 1 | Spool 2

STG 1 | STG 2 | STG 3 | STG 4 | STG 5 | STG 6 | STG 7

	Hub		Tip	
	Ts	Ps	Ts	Ps
Rotor In	633.499	25.435	667.964	30.617
Rotor Ex	702.506	34.818	759.586	45.767
Stator In	703.595	35.008	757.962	45.426
Stator Ex	728.395	38.945	764.575	46.147
Strut In				
Strut Ex				

Stream No 1

Clear Comp | Clear Turb

Assign Comp | Assign Turb

Stream path type

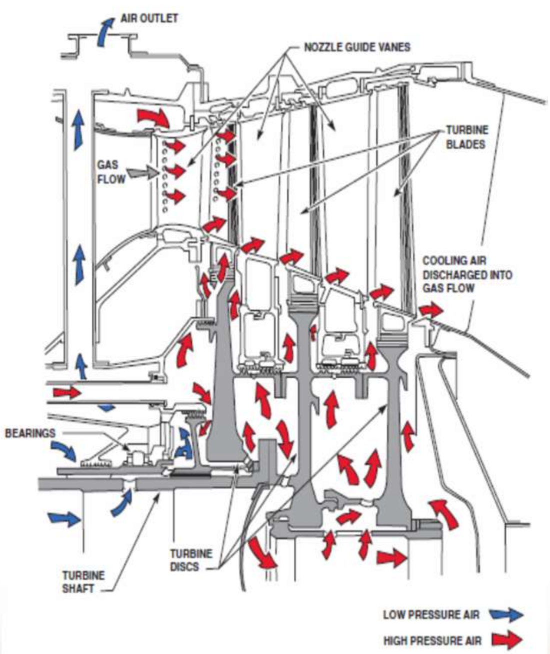
delPo min 0.0

Turbine IAS Allocation

Spool 1 | Spool 2

STG 1 | STG 2

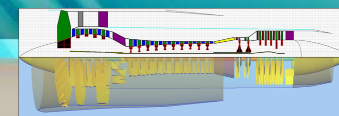
	Hub		Tip	
	Ts	Ps	Ts	Ps
Stator In	2226.420	252.156	2231.910	254.655
Stator Ex	1988.440	154.575	2041.850	171.876
Rotor In	1995.900	156.909	2054.250	176.095
Rotor Ex	1888.750	123.614	1909.490	129.138
Strut In				
Strut Ex				

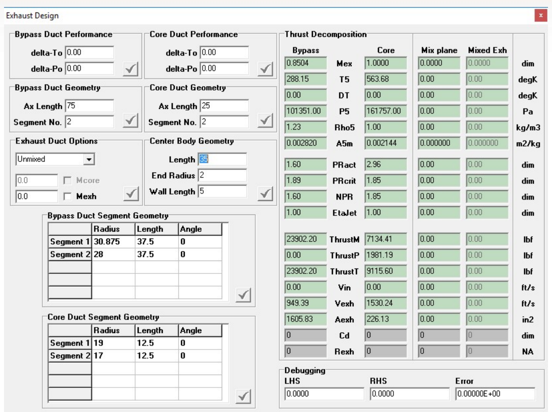


The engineer:

- Executes the preliminary and detailed air-system allocation between compressor and turbine stages
    - Bearings
    - Fixings
    - Seals
    - Hydraulic fluid systems (lubrication and cooling)
    - Fuel systems
    - Hot gas path ingestion
    - Sand particle removal

Duct design

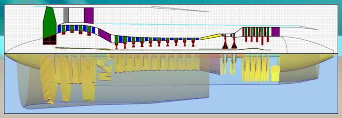


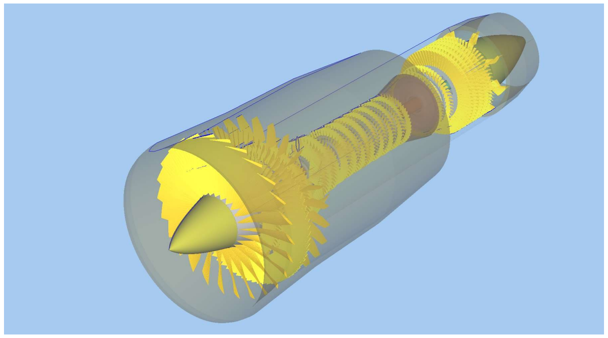


The engineer:

- Creates different exhaust geometries
  - Unforced unmixed
  - Unforced mixed
- Nacelle design
  - Axisymmetric
  - Non-axisymmetric

Overall Design





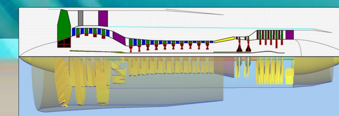
The engineer:

- Gathers all 2D and 3D designs from the disciplines
- Creates full 2D and 3D representations of the overall design
- Checks for clashes
- Weight calculations
- Integrated hot-to-cold conversion

Gas turbine design

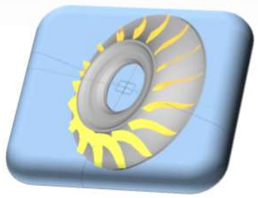
IT DOESN'T END THERE

Other activities



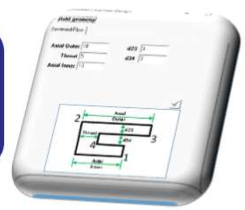
Complex integrated Performance analysis

Centrifugal compressor design



Shaft dynamics

Combustion design



- Cost analysis
- Testing
- Lifing Analysis
- Sales
- Digital twin (production data analysis)
- After Service
- Procurement
- Production
- Manufacturing
- R & D
- **Etc …**

Any questions?

Turbomachinery Lecture Series

Gas Turbine Engine Design & Development

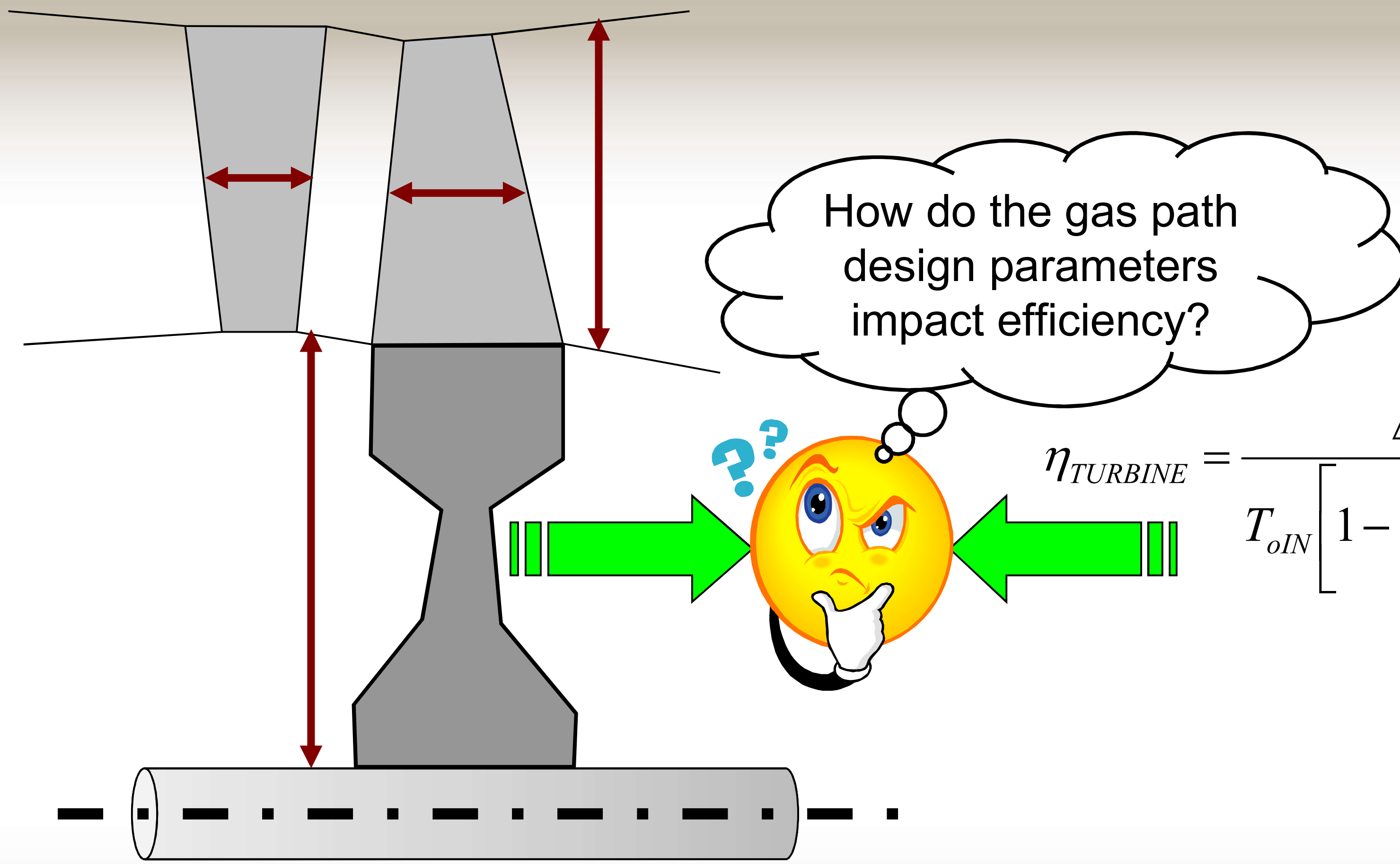
PART 2

"A mean line efficiency prediction method is the sum of a large number of loss components. While some of them may prove to be quantitatively imperfect, the manner in which they are combined may cause errors to cancel. The final proof of a loss system must be its ability to correctly predict the efficiencies of well documented turbines [or compressors]"- **Kacker & Okapuu**

Aerodynamics

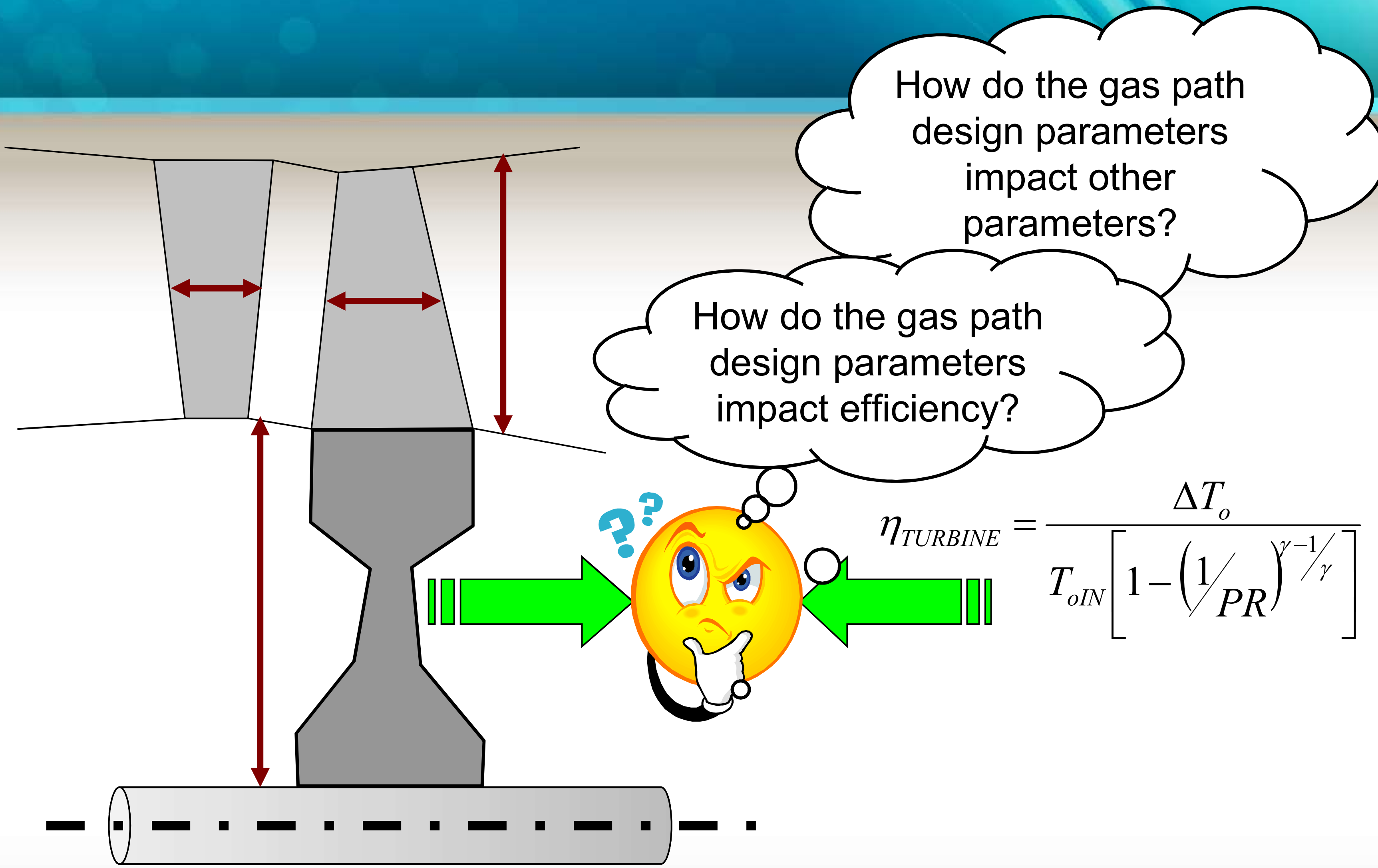
TURBINES

Aerodynamics and loss modeling



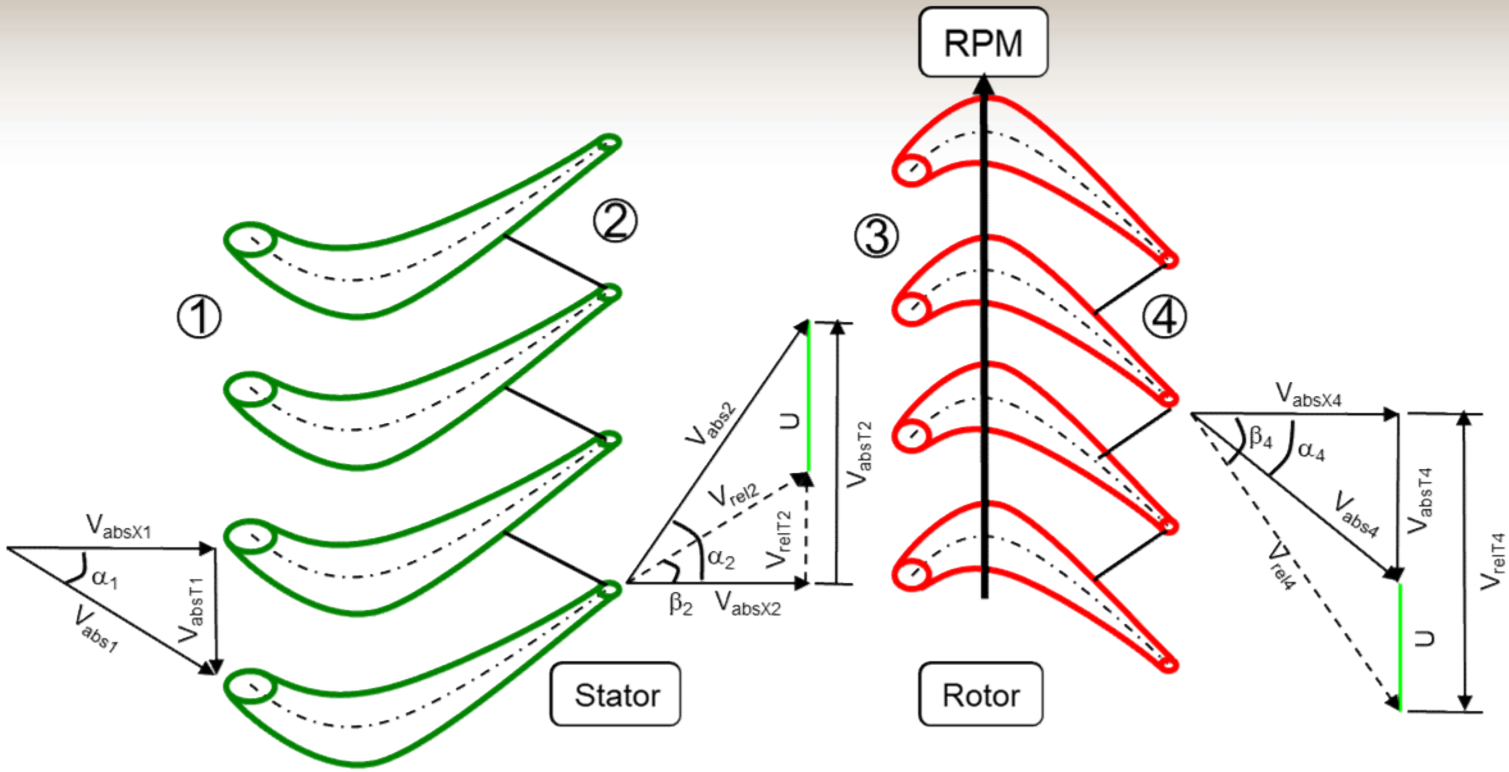
$$\eta_{TURBINE} = \frac{\Delta T_o}{T_{oIN}\left[1-\left(\frac{1}{PR}\right)^{\gamma-1/\gamma}\right]}$$

Aerodynamics and loss modeling

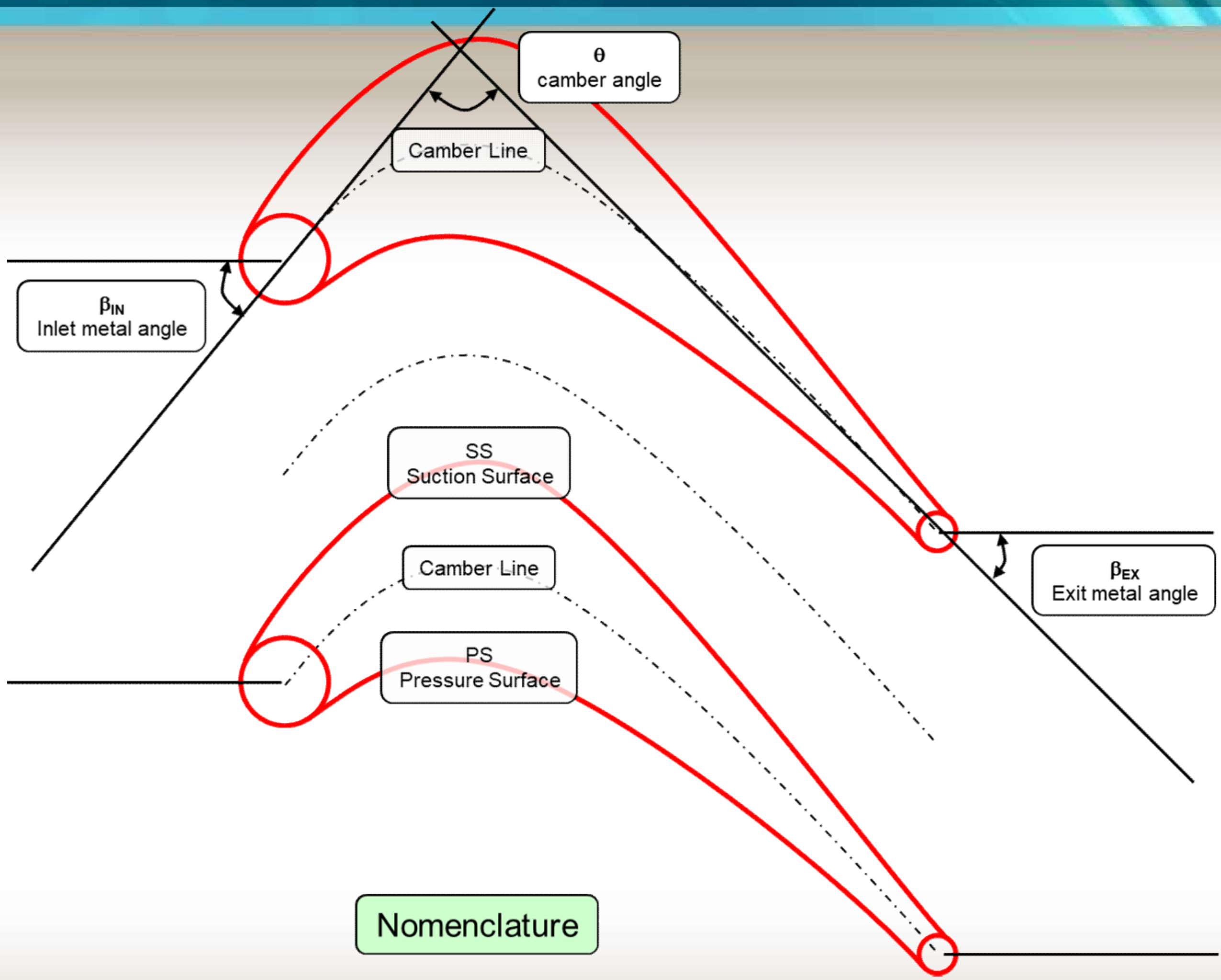


$$\eta_{TURBINE} = \frac{\Delta T_o}{T_{oIN}\left[1-\left(\frac{1}{PR}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Turbine Stage

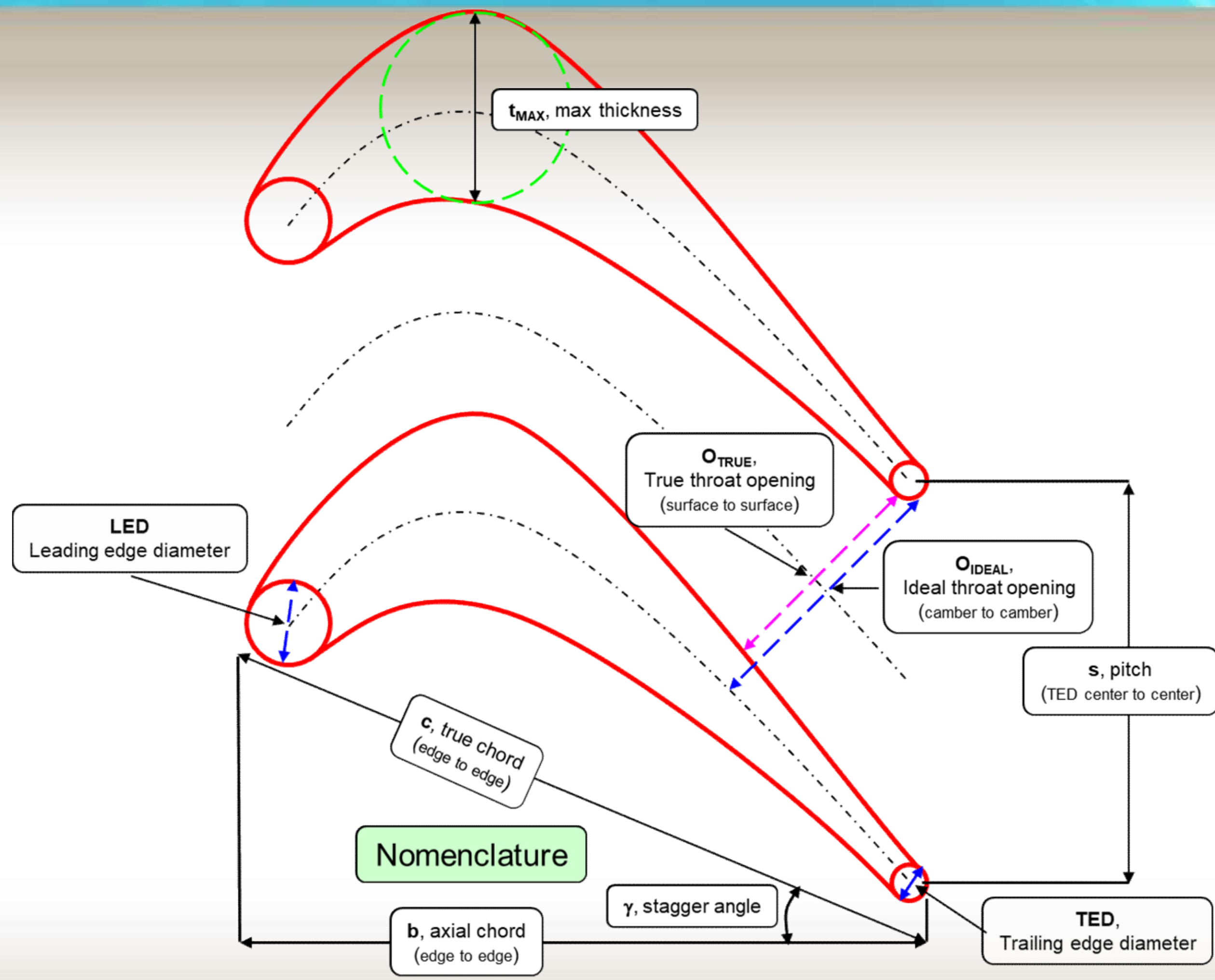


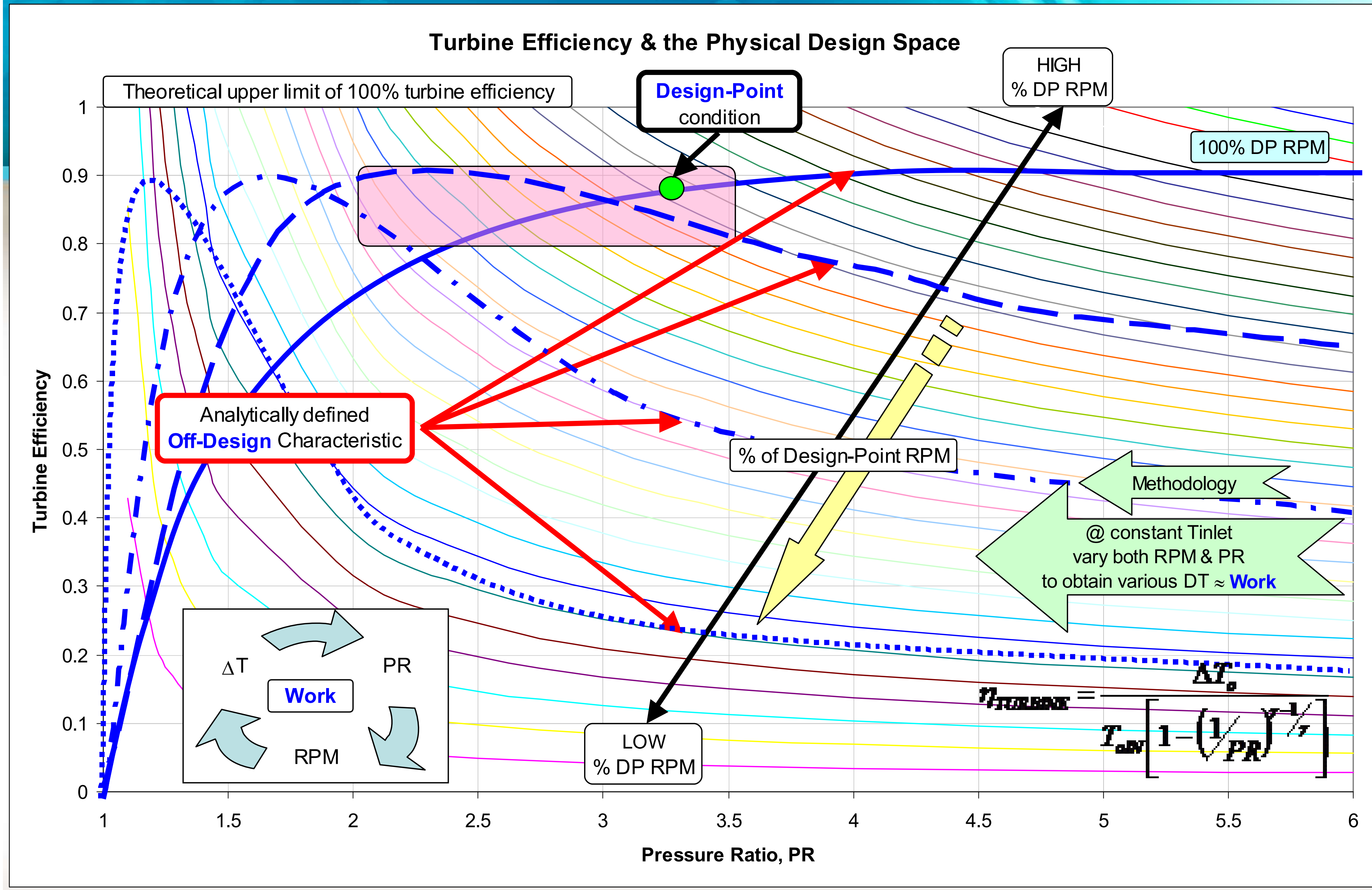
Turbine Blade Design



Nomenclature

Turbine Blade Design

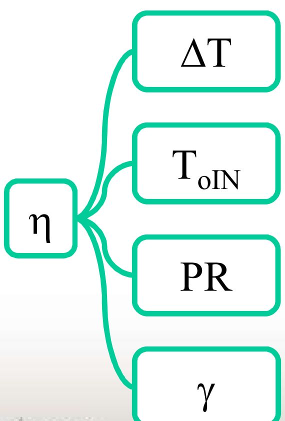



Turbine Efficiency & the Physical Design Space
Theoretical upper limit of 100% turbine efficiency
Design-Point condition
HIGH % DP RPM
100% DP RPM
Analytically defined Off-Design Characteristic
% of Design-Point RPM
Methodology
@ constant Tinlet vary both RPM & PR to obtain various DT ≈ Work
ΔT
PR
Work
RPM
LOW % DP RPM
$\eta_{TURBINE} = \frac{\Delta T_o}{T_{oIN}\left[1-\left(\frac{1}{PR}\right)^{\gamma-1/\gamma}\right]}$
Turbine Efficiency
Pressure Ratio, PR
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6

$$\eta_{TURBINE} = \frac{\Delta T_o}{T_{oIN}\left[1-\left(\frac{1}{PR}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Turbine Efficiency

After much algebraic manipulation

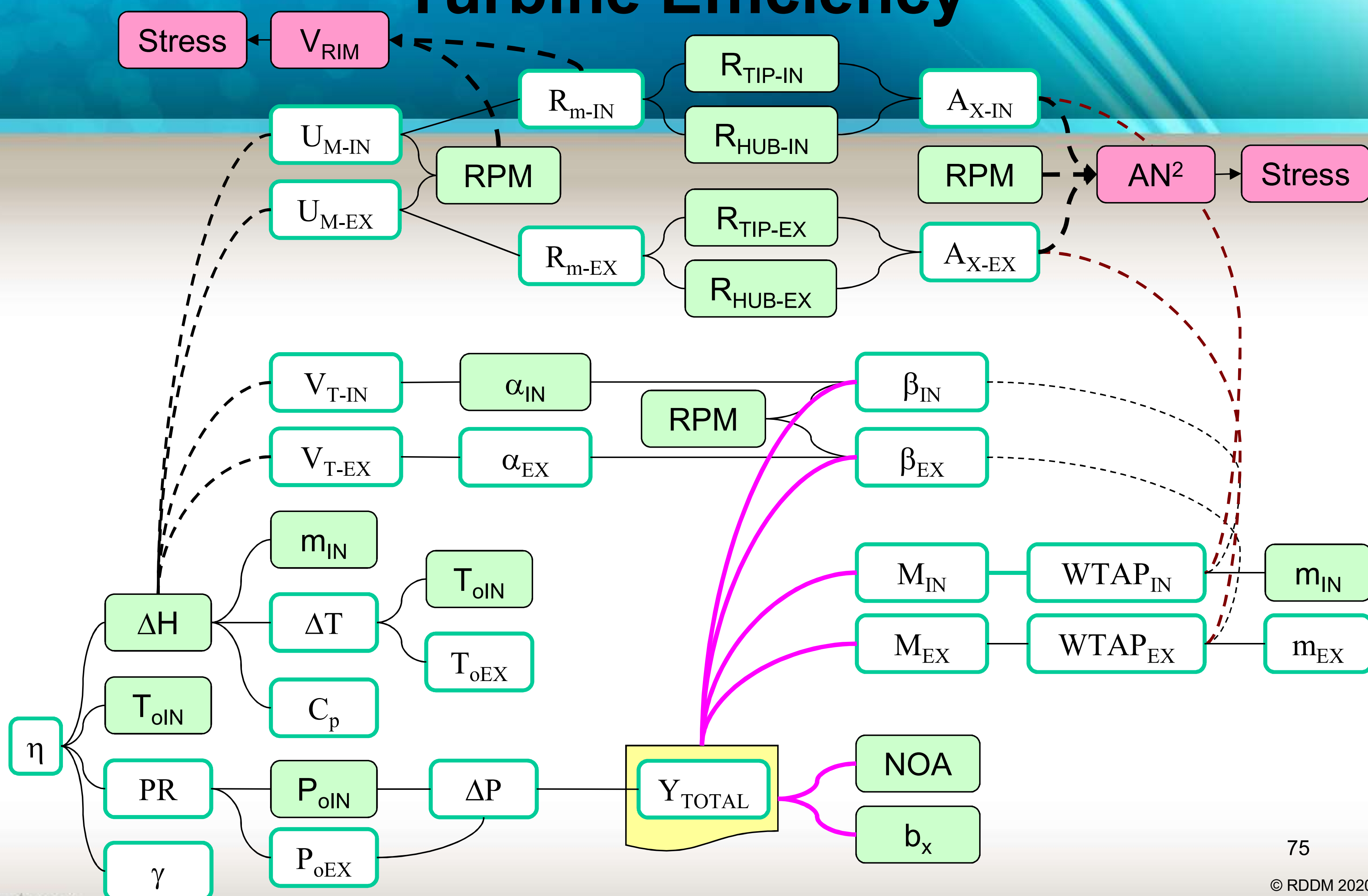


$$\Delta H = \dot{m}\left(C_p T_{oIN} - C_p T_{oEX}\right) = \dot{m} C_p \left(T_{oIN} - T_{oEX}\right) = \dot{m} C_p \Delta T$$

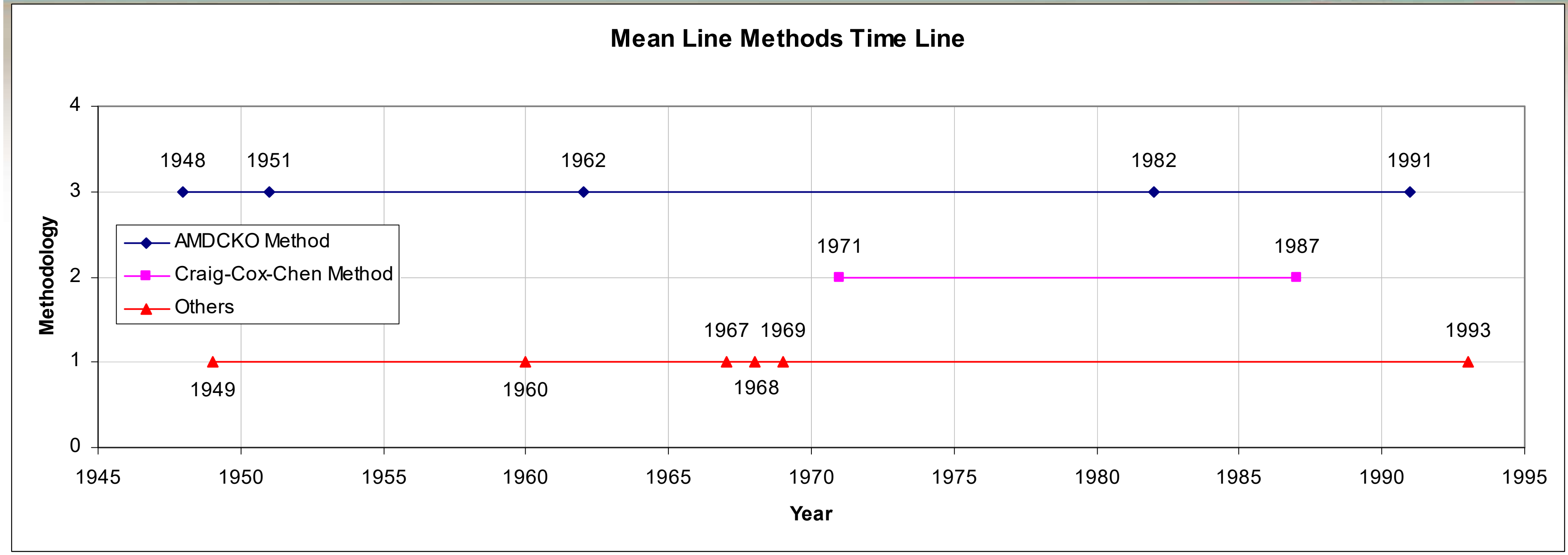
$$\left(C_p T_{oIN} - C_p T_{oEX}\right) = \left(V_{TANG-IN} U_{IN} - V_{TANG-EX} U_{EX}\right) = \left[V_{TANG-IN}\left(\omega R_{IN}\right) - V_{TANG-EX}\left(\omega R_{EX}\right)\right]$$

$$\eta_{TURBINE} = \frac{\Delta T_o}{T_{oIN}\left[1-\left(\frac{1}{PR}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

Turbine Efficiency



Turbine Loss Models



Ainley &Matheison (AM) $Y_{TOTAL} = (Y_P + Y_S + Y_{TC})Y_{TE}$ (1951)

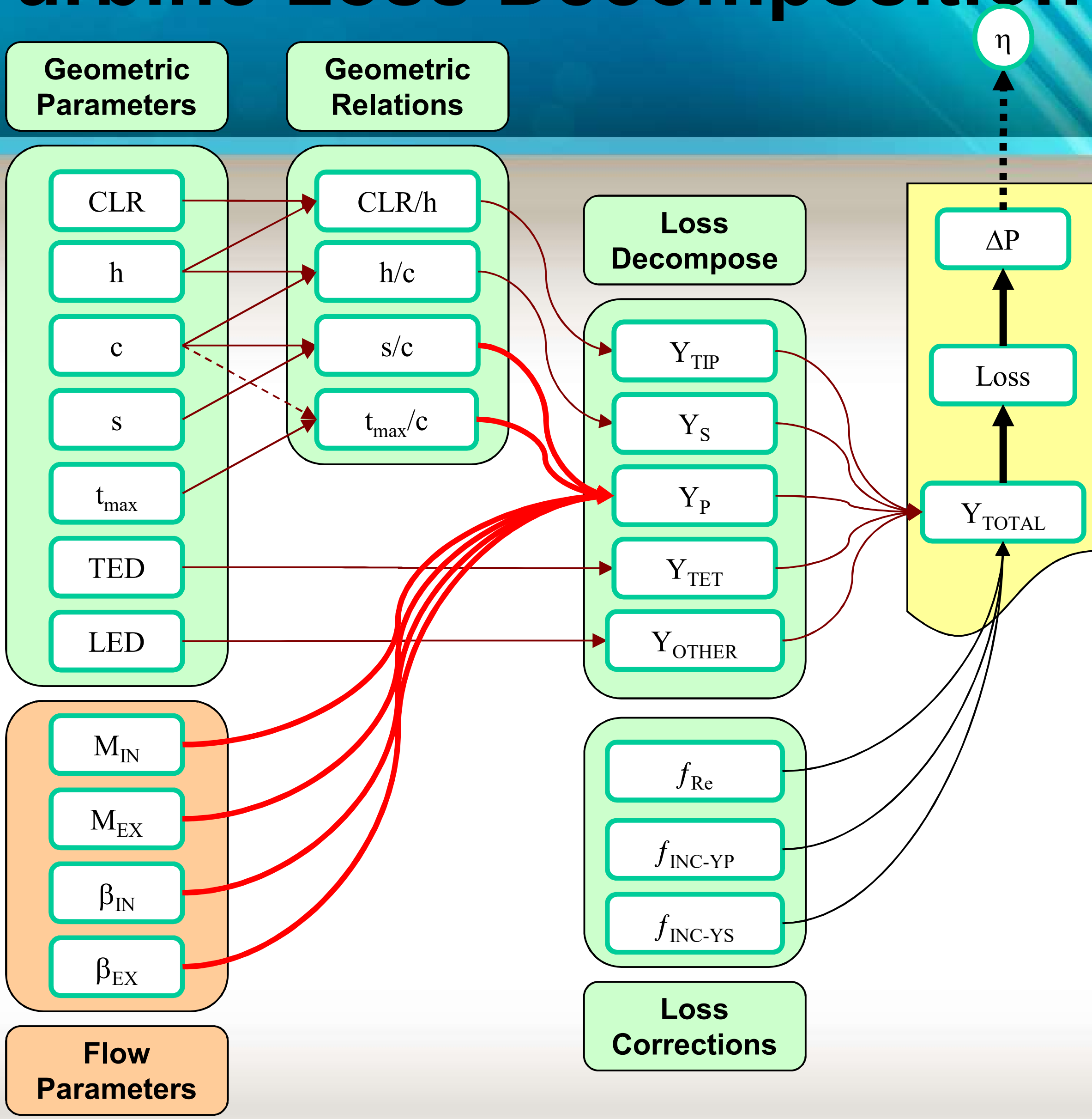
Dunhum & Came (DC) $Y_{TOTAL} = [(Y_P + Y_S)REFAC + Y_{TC}]Y_{TE}$ (1970)

Kacker &Okapuu (KO) $Y_{TOTAL} = Y_P f_{(\mathrm{Re})} + Y_S + Y'_{TE} + Y_{TC}$ (1982)

1945 Zweifel

$$\therefore \psi_T = 2 \cdot \cos^2 \beta_2 [\tan \beta_2 + \tan \beta_1] \cdot \frac{s}{b_x}$$

Turbine Loss Decomposition



Turbine Loss Decomposition

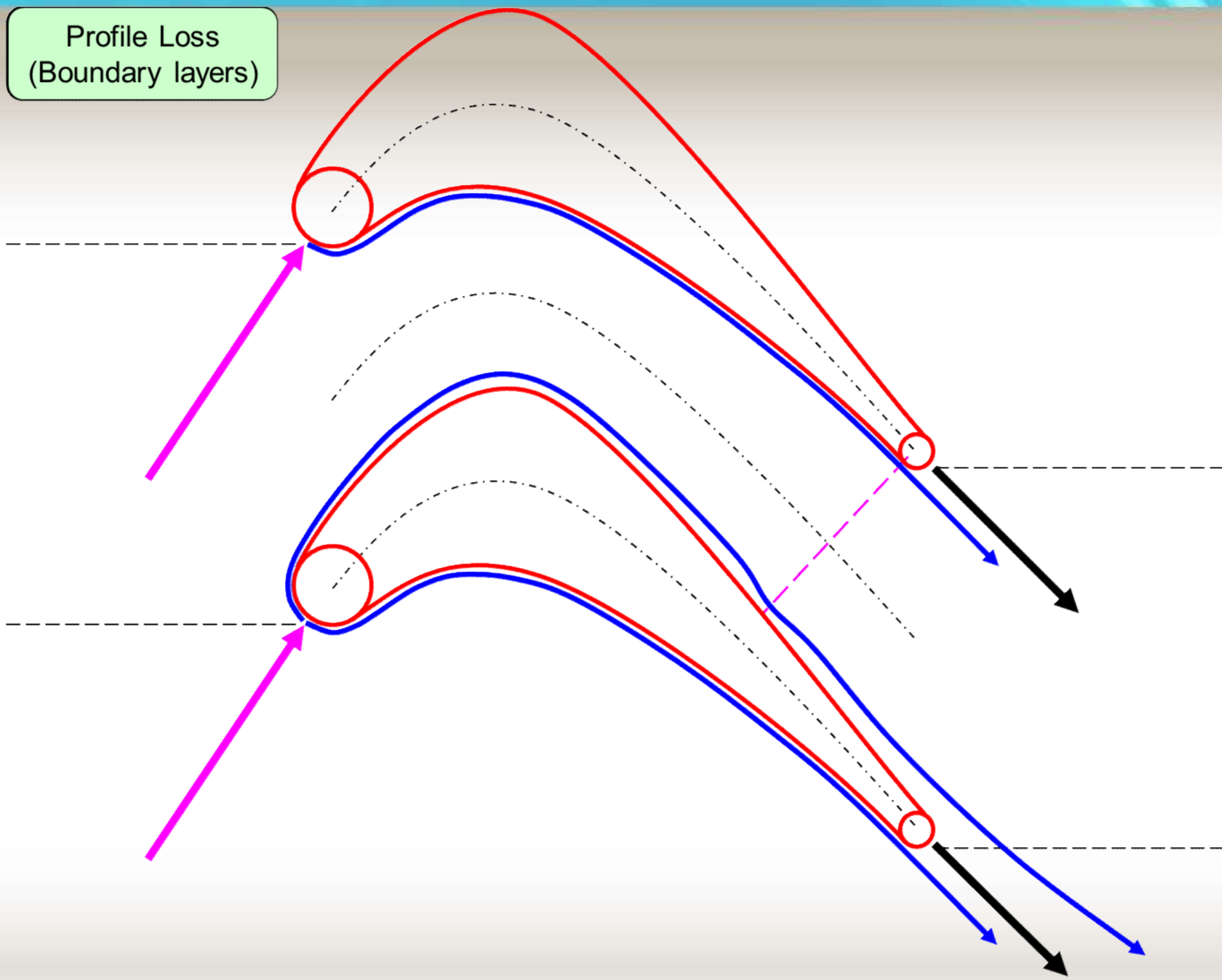
Turbine losses can be classically decomposed into the following loss components

- Profile
- Secondary
- Trailing Edge
- Tip Clearance
- Other

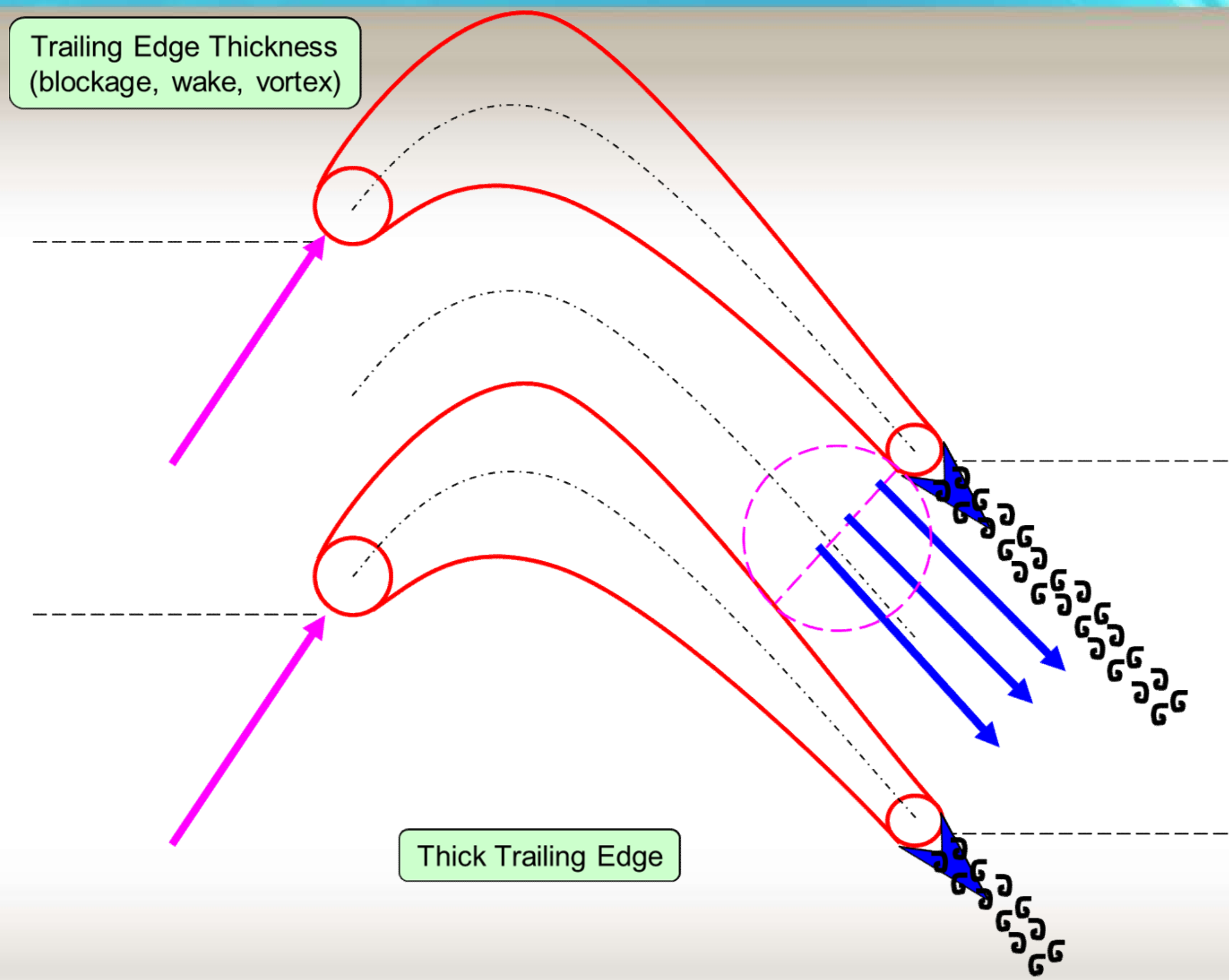
- Y_P
- Y_S
- Y_{TET}
- Y_{TIP}
- Y_{OTHER}

Both geometric parameters and flow values have an impact on loss.

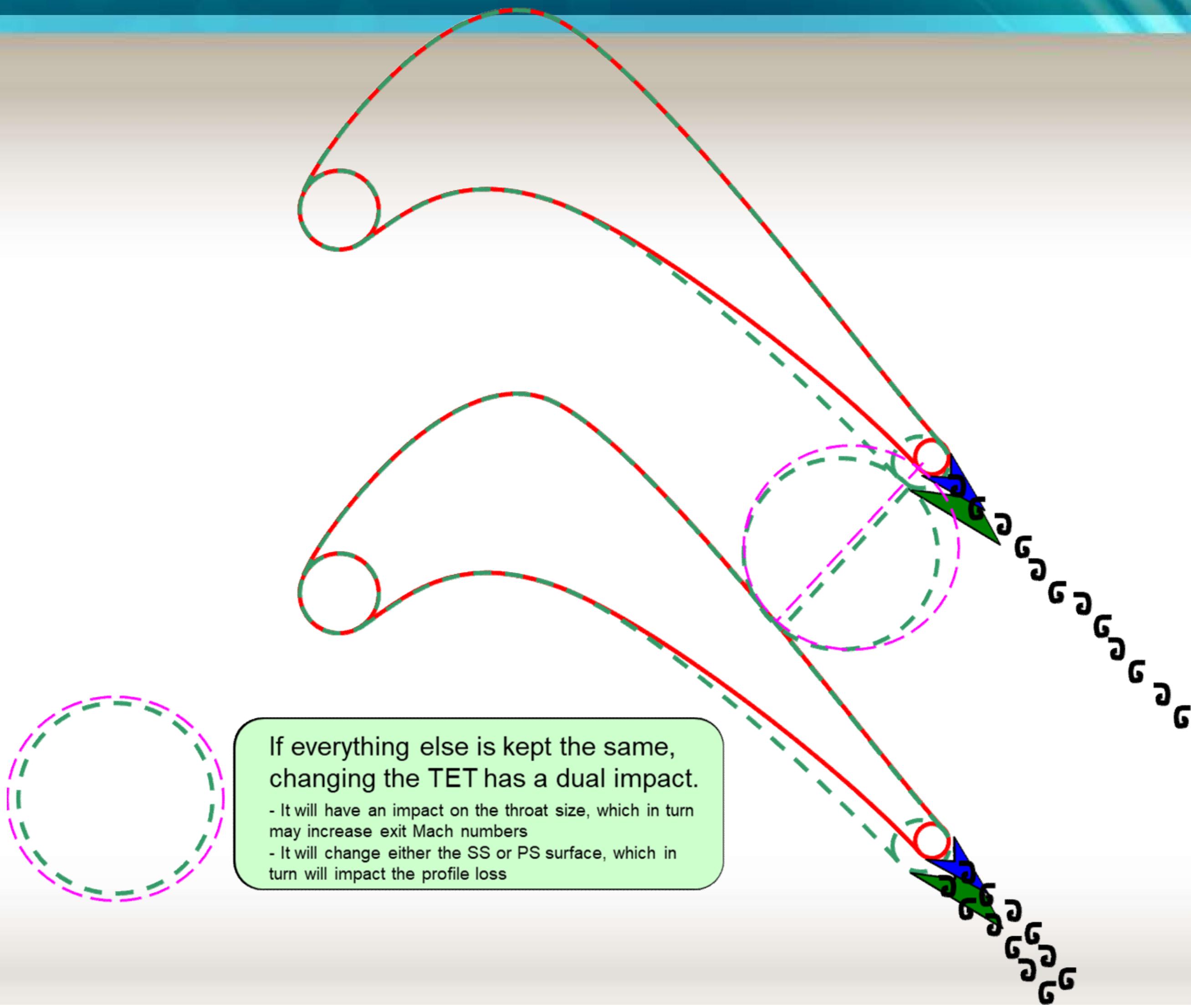
Turbine Losses



Turbine Losses



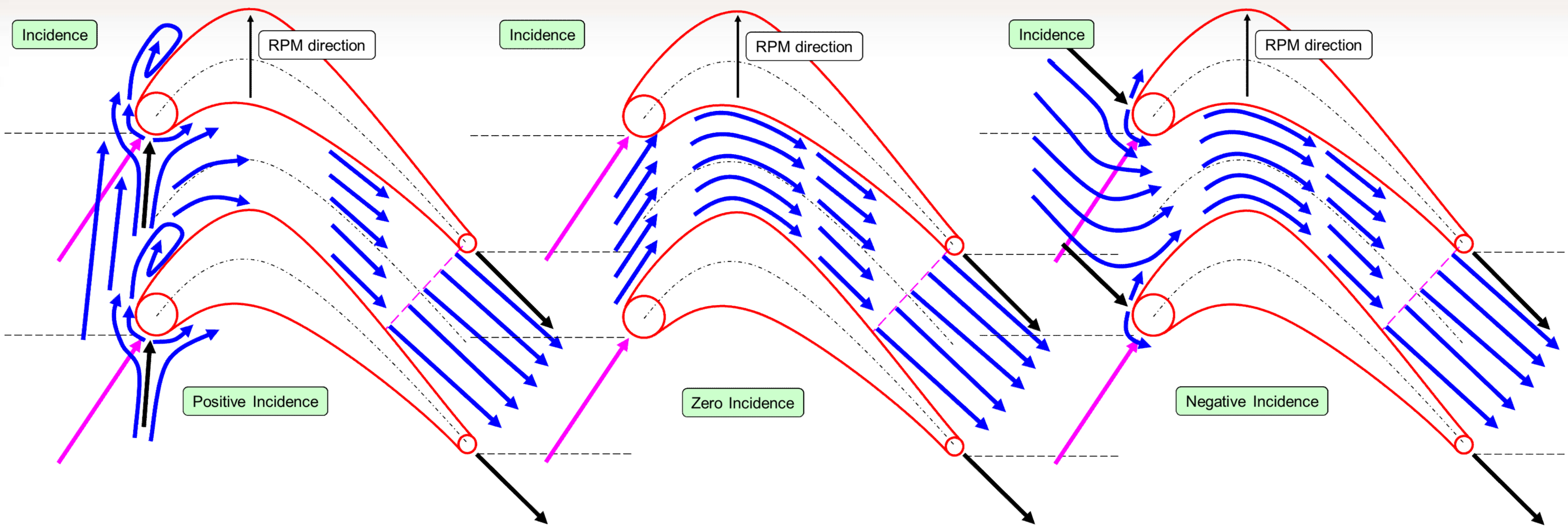
Turbine Losses



If everything else is kept the same, changing the TET has a dual impact.

- It will have an impact on the throat size, which in turn may increase exit Mach numbers
- It will change either the SS or PS surface, which in turn will impact the profile loss

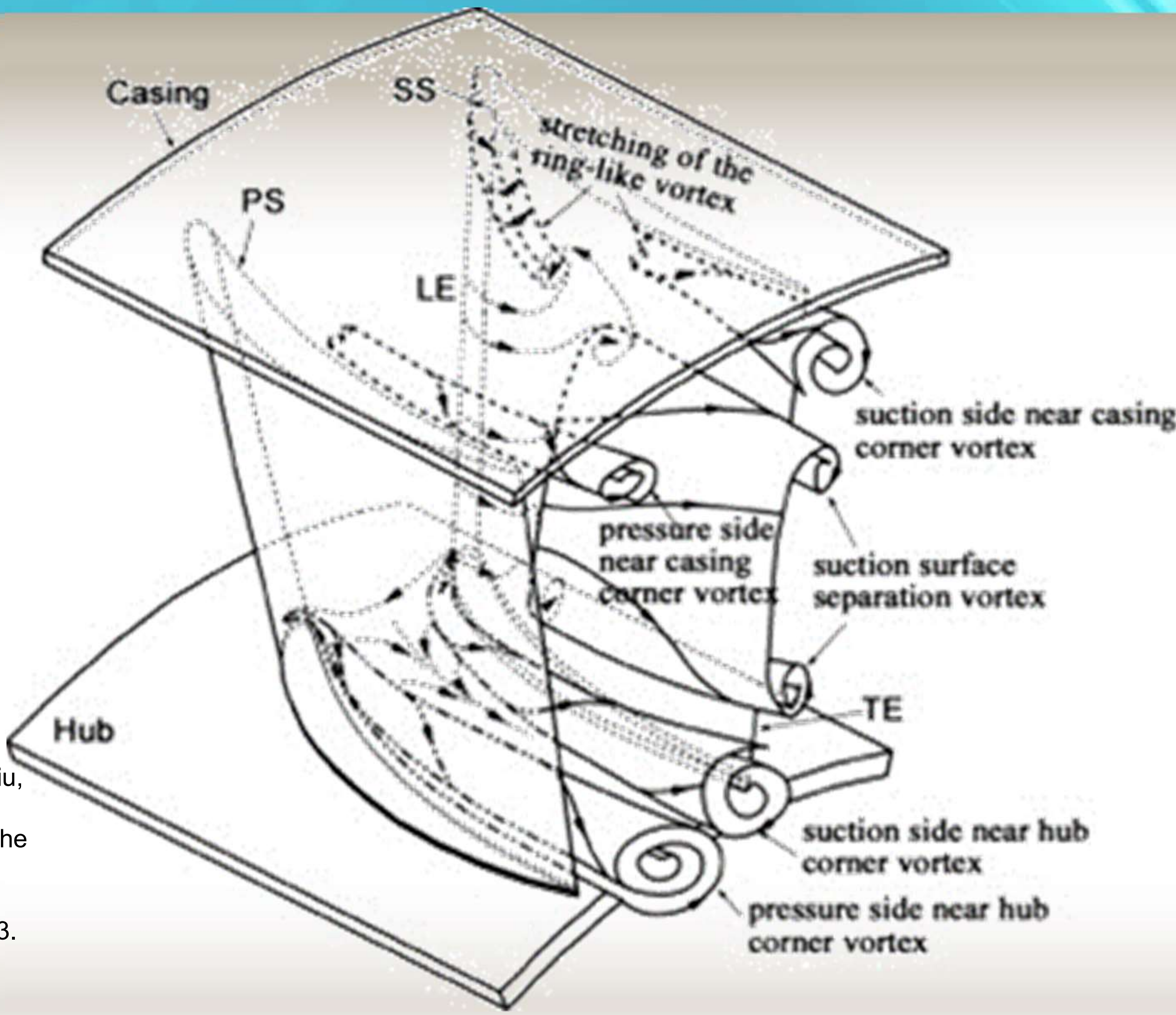
Turbine Losses



Aerodynamics

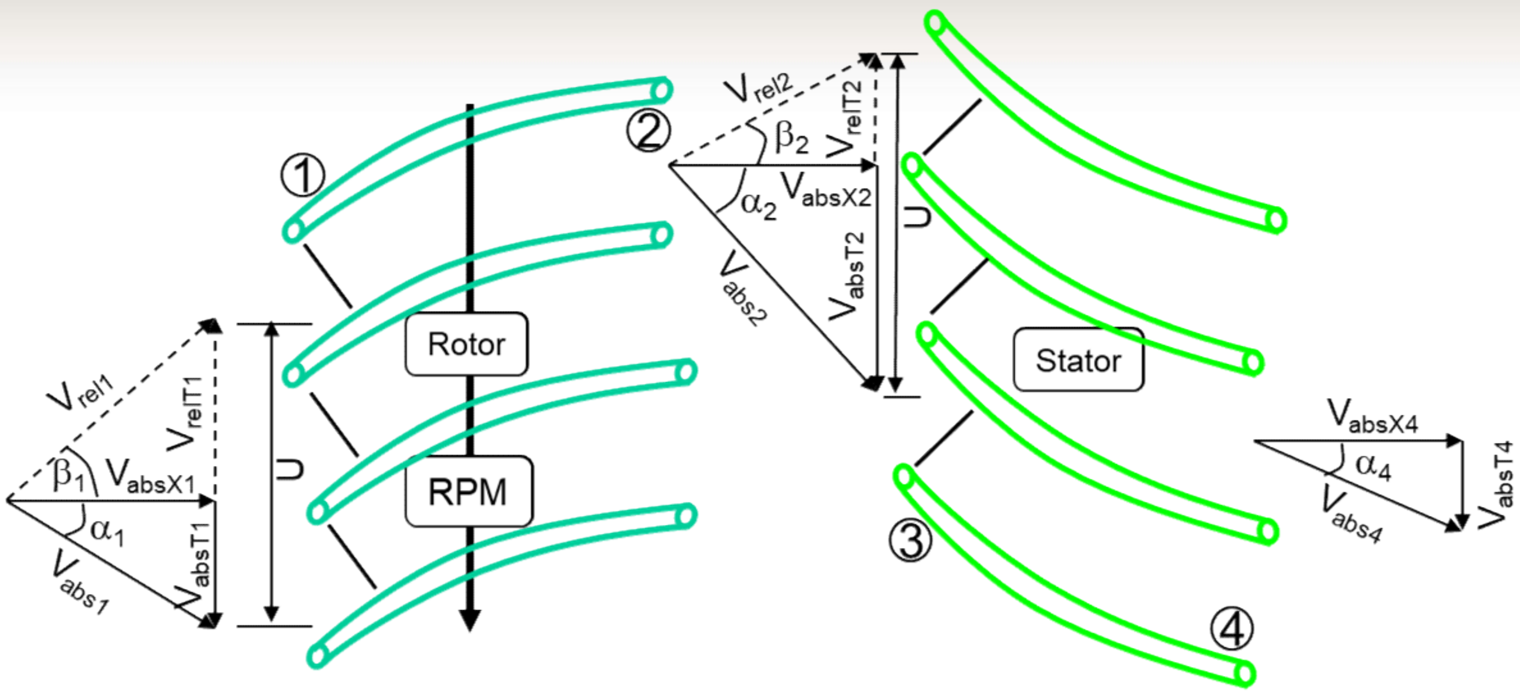
COMPRESSORS

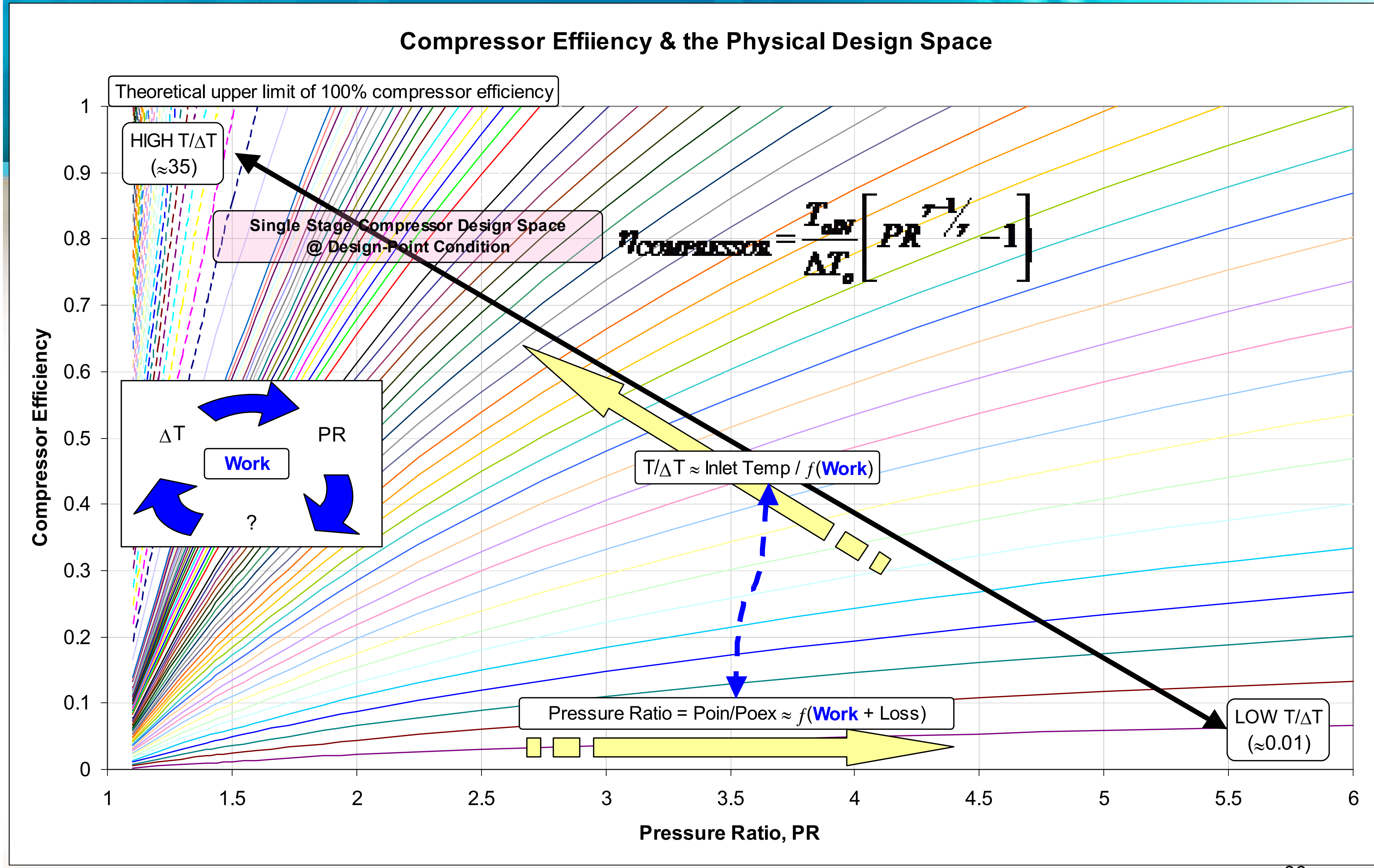
Compressor Loss Mechanisms



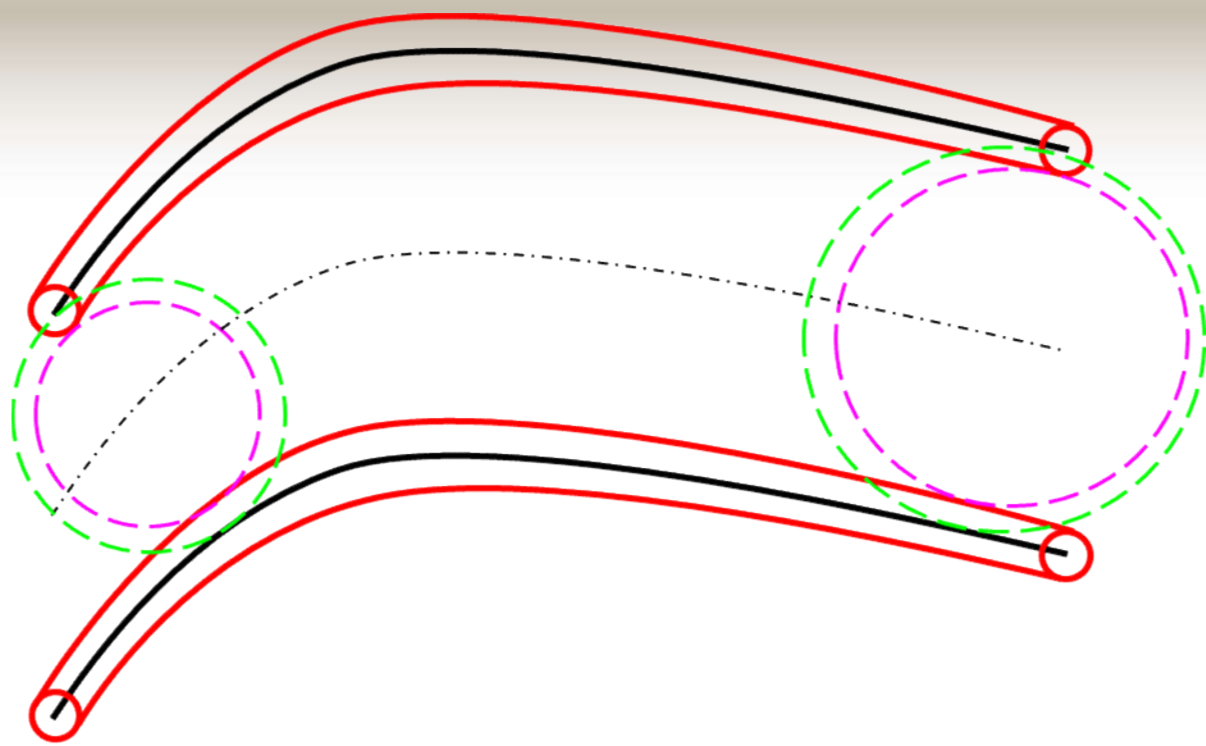
REF: Yu, X., Z. Zhang, and B. Liu, The evolution of the flow topologies of 3D separations in the stator passage of an axial compressor stage. Experimental Thermal and Fluid Science, 2013. 44: p. 301-311.

Compressor Stage




Compressor Effiiency & the Physical Design Space
Theoretical upper limit of 100% compressor efficiency
HIGH T/ΔT (≈35)
Single Stage Compressor Design Space @ Design-Point Condition
$\eta_{COMPRESSOR} = \frac{T_{oIN}}{\Delta T_o}\left[PR^{\gamma-1/\gamma} - 1\right]$
ΔT
PR
Work
?
T/ΔT ≈ Inlet Temp / ƒ(Work)
Pressure Ratio = Poin/Poex ≈ ƒ(Work + Loss)
LOW T/ΔT (≈0.01)
Compressor Efficiency
Pressure Ratio, PR
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6

Compressor Blade Design



Thin vs Thick Airfoil Assumption

Compressor mean-line model

"Bladed mass flow equation"

$$\frac{\dot{m}\sqrt{T_{o0}}}{P_{o0} C_D A \cos(\alpha_0)} = \frac{M\sqrt{\gamma/R_g}}{\left[1+\frac{(\gamma-1)}{2}M^2\right]^{(\gamma+1)/2(\gamma-1)}}$$

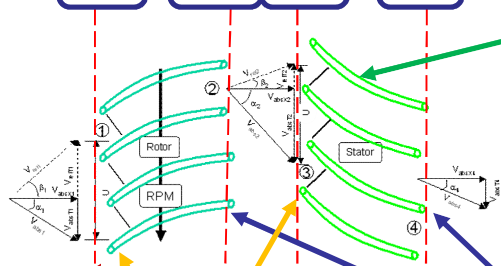
Blockage factor used to mimic Boundary layer thickness

Blockage factor used to mimic Airfoil thickness

Blockage factor used as "go-to" parameter for PR match.

Cd may be used at every mean-line calculation plane

Cd | Cd | Cd | Cd



Actual airfoil thickness ignored

Literature shows mainly using idealized thin cambered airfoil

Constant tip clearance

Literature shows that tip clearance remains fixed in a ML model

Incidence at LE

Directly obtained from ML solution

Deviation at TE

Literature has shown wide-spread use of Carter's rule

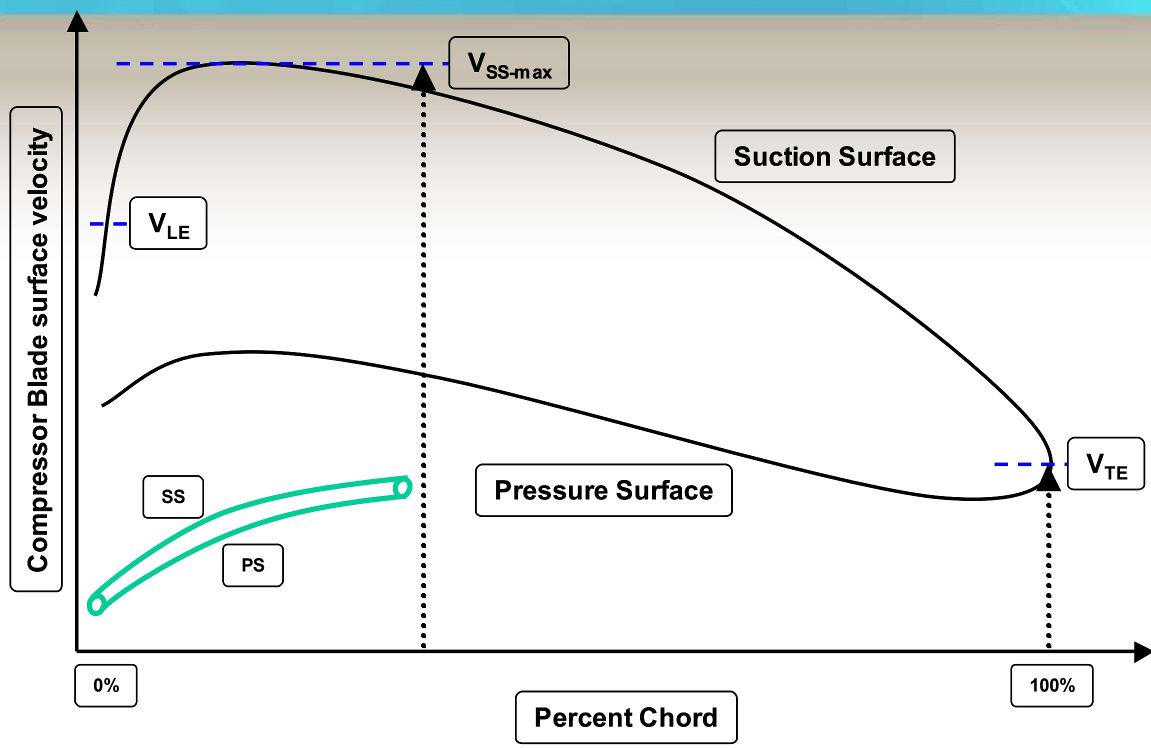
Remains constant through OD conditions

Compressor loss models

Author	Formula
Lieblein (1953)	$\omega_{TOTAL} = \omega_P$
Koch & Smith (1976)	$\omega_{total} = \omega_{P\&TE} + \omega_{EW\&TC} + \omega_{shock} + \omega_{PS-shrouds}$ *(interpreted formula from reference)*
Barbosa (1987)	$\omega_{TOTAL} = \omega_P f_{Re} + \omega_S + \omega_{SH} + \omega_{COR}$
Wright & Miller (1991)	$\omega_{total} = \left(\omega_p\|_{Re=10^6} + \omega_{EW\&TC}\right) f(Re) + \omega_{shock}$ *(interpreted formula from reference)*
Bloch, Copenhaver, O'Brien (1997)	$\bar{\omega} = \omega_{profile} + \omega_{shock}$
Cahill (1997)	$\omega_{TOTAL} = \omega_P + \omega_S + \omega_{shock}$
Lynette Smith (1999)	$\omega = (\varpi_{min} + \varpi_M)\left[1 + \left(\frac{i - i_{min}}{W}\right)^2\right]$
Ramakdawala (2001)	$\omega_{TOTAL} = \omega_{Profile} + \omega_{EW\&TC} + \omega_{Shock}$
Boyer (2001)	$\omega = \left(\varpi_{min} + \varpi_M + \varpi_{tip} + \varpi_{hub}\right)\left[1 + \left(\frac{i - i_{min}}{W}\right)^2\right]$
van Antwerpen (2007)	$\omega = \omega_p^* \left(\frac{\omega}{\omega_i}\right)_{inc} \left(\frac{\omega}{\omega_i}\right)_{Re} \left(\frac{\omega}{\omega_i}\right)_{Ma} + \omega_s \left(\frac{\omega}{\omega_i}\right)_{Re} + \omega_a$, for $i > i_{min}$ $\omega = \omega_p^* \left(f\left(\frac{\omega}{\omega_i}, \Phi\right)\right)_{inc} \left(\frac{\omega}{\omega_i}\right)_{Re} + \omega_s \left(\frac{\omega}{\omega_i}\right)_{Re} + \omega_a$, for $i < i_{min}$
Falck (2008)	$\omega_{TOTAL} = \omega_P + \omega_{ew}$
Veres (2009)	$\omega_{TOTAL} = \omega_P + \omega_{shock}$
Benini (2010)	$\zeta = \zeta_{(M=0)} \chi_R \chi_M + \zeta_{shock} + \zeta_S + \zeta_\delta + K_M\left(i - i_{ref}\right)^2$

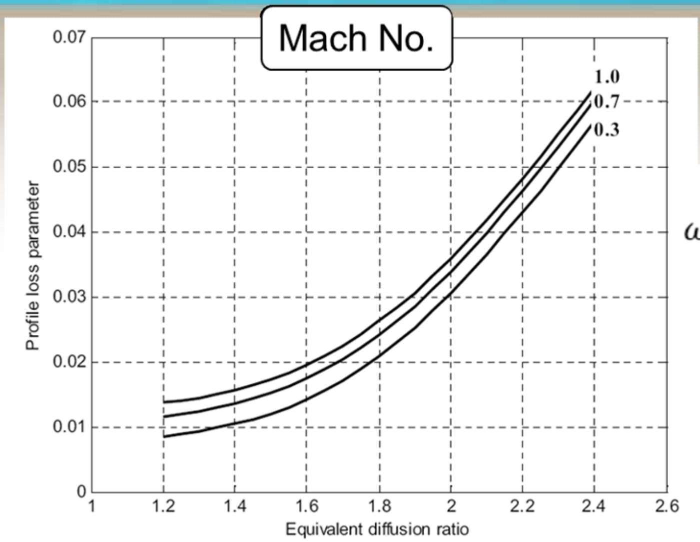
Other references of interest

- Steinke
- Howell & Calvert
- Schobeiri
- Denton
- AGARD
- Etc …



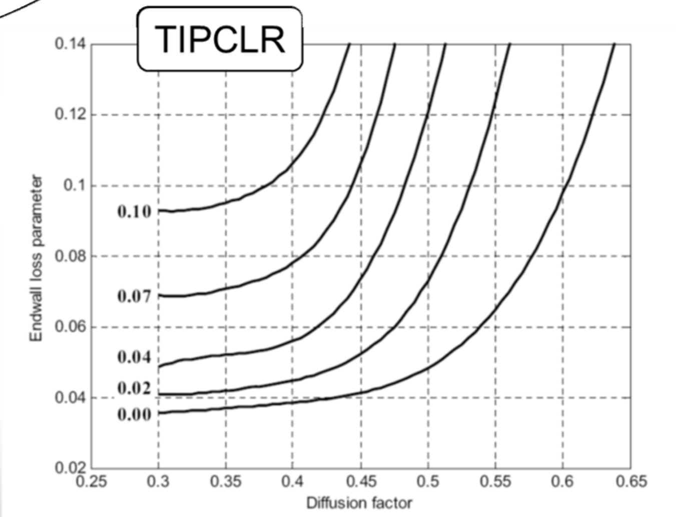
$$\text{de Haller No.} = \left(\frac{V_{rel2}}{V_{rel1}}\right)_{rotor}, \left(\frac{V_{abs4}}{V_{abs3}}\right)_{stator} \qquad DF = \frac{V_{SS-max} - V_{TE}}{V_{LE}} \qquad DR = \frac{V_{SS-max}}{V_{TE}} \qquad V_{rel,SS-max} = V_{rel,LE} + \frac{\Delta V_{relT}}{2}\frac{s}{c}$$

Compressor loss



$$\omega_p 0.5 \frac{V_1^2}{V_2^2} cos(\alpha_2) = f(M_1, D_{eq})$$

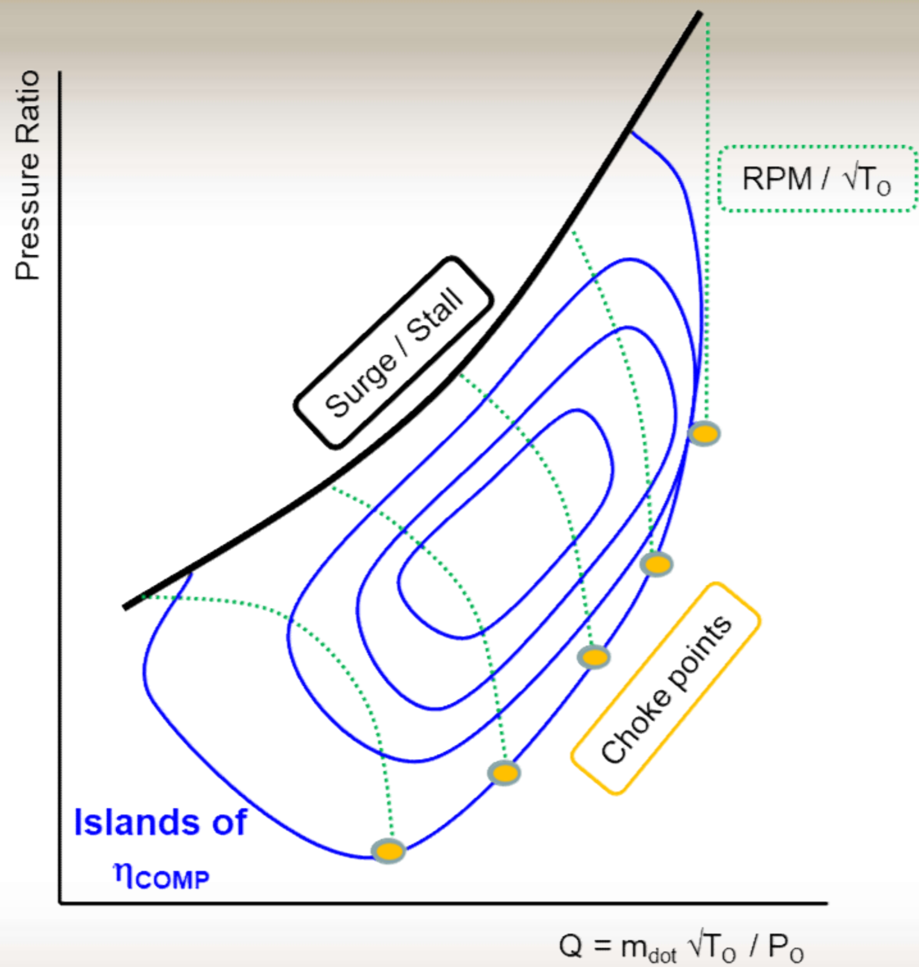
$$\omega_{ew} \frac{h}{c} \frac{V_1^2}{V_2^2} = f\left(\frac{\varepsilon}{c}, DF\right)$$



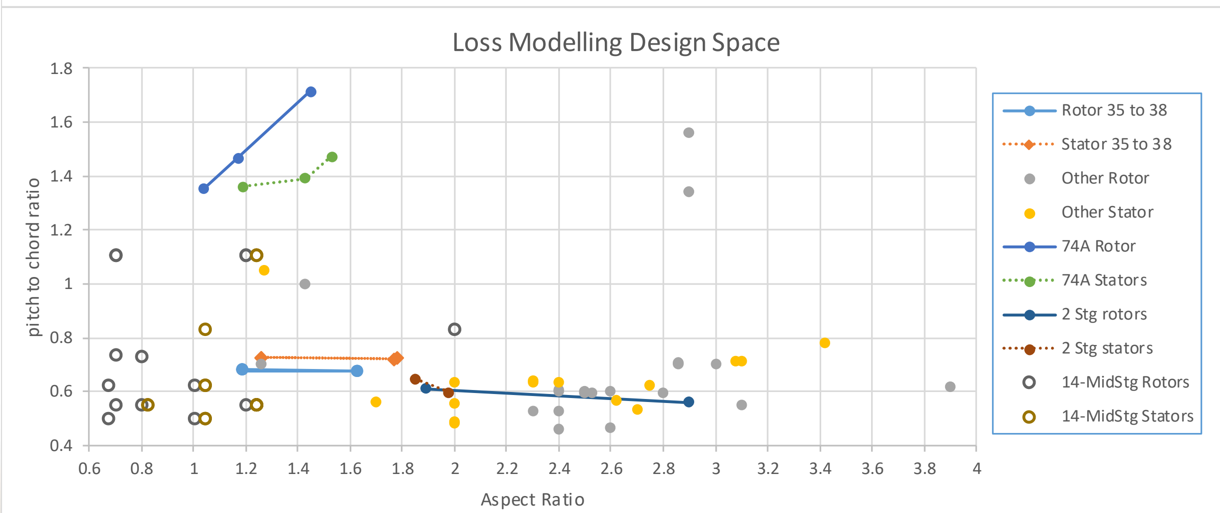
$$\omega = \omega_{ew} + \omega_p$$

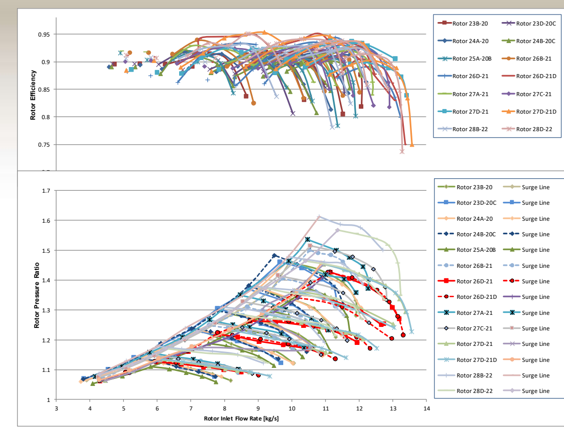
$$\omega = \frac{\Delta p_0}{p_{01} - p_1}$$

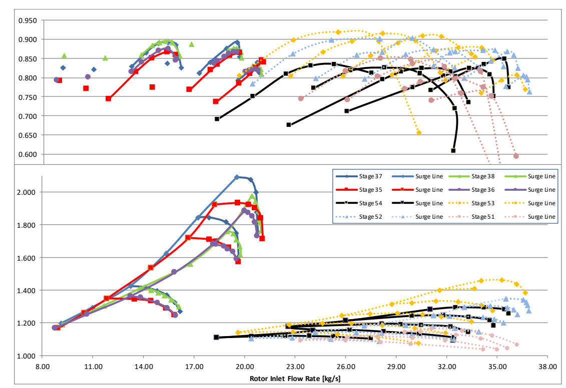
Compressor Performance Chart



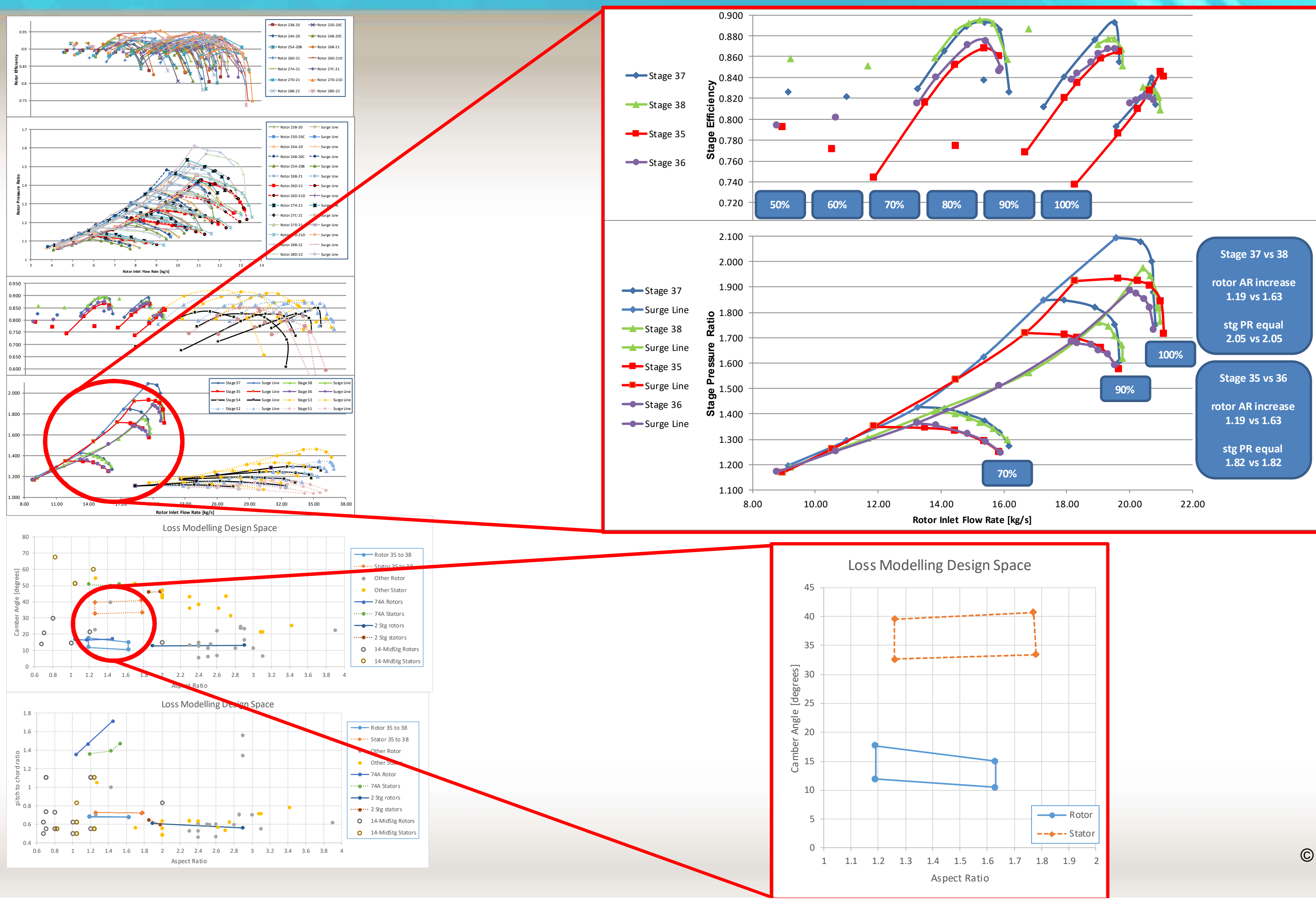
Compressor Data



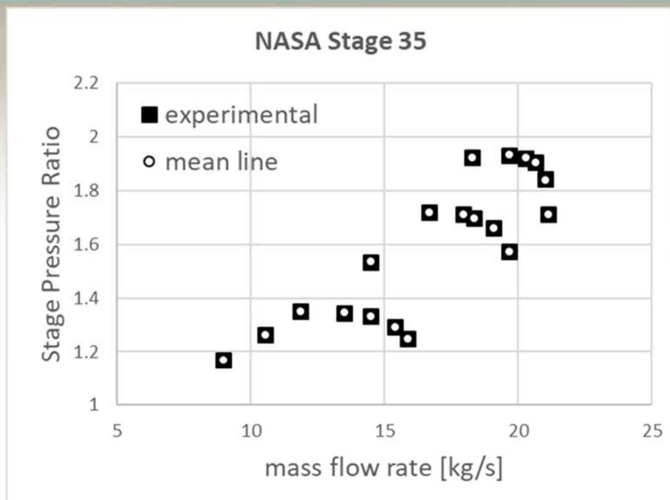


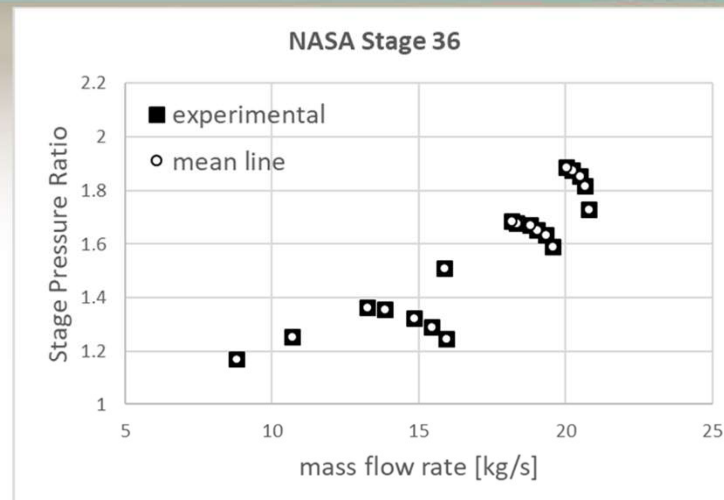


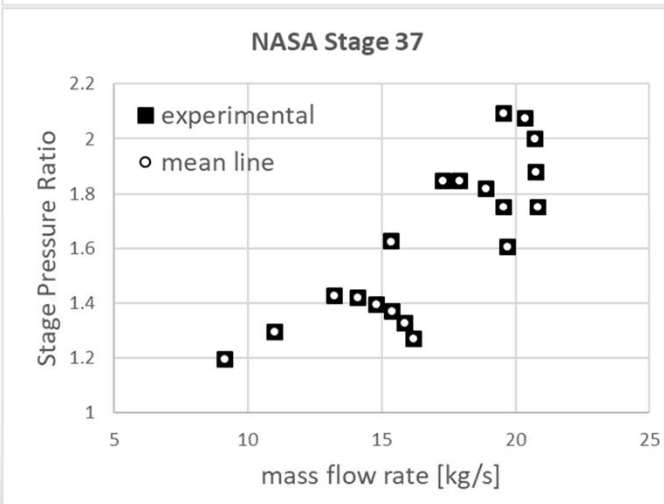
Compressor Loss Modeling

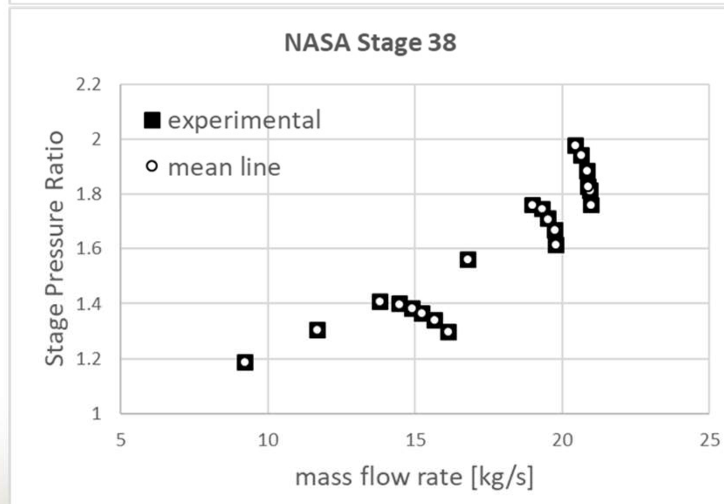


MDIDS-GT modeling







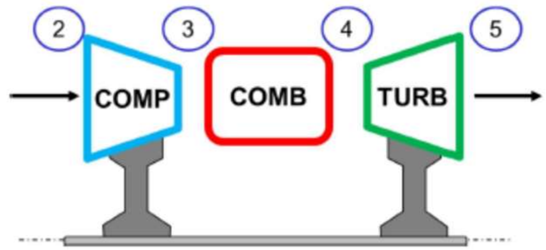


Calculations

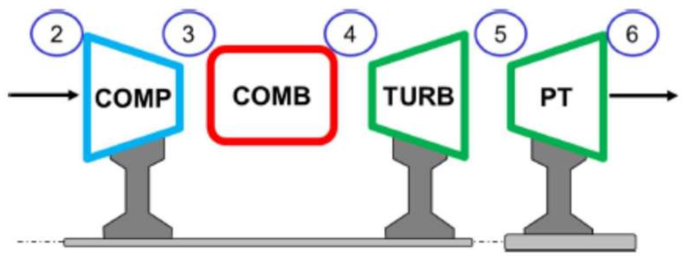
PERFORMANCE

Cycle Calculation

A. Compte tenu de la section "core" de turbine à gaz suivant, et les données liées, déterminer les températures et les pressions des entrées et des sorties, puis le taux de dilution (fuel-air ratio), et le SFC.



B. Si une turbine de puissance ("power turbine") est ajoutée, trouver les températures, les pressions, et le SFC du moteur suivant.



Air froide	**Air chaude**	**Carburant**
$\gamma = 1.4$ $c_p = 1004.5$ J / kg K $R_{gas} = 287$ J / kg K	$\gamma = 1.33$ $c_p = 1156.7$ J / kg K $R_{gas} = 287$ J / kg K	$Q = 46.2 \times 10^6$ J / kg K $C_p = 2.01 \times 10^3$ J / kg K $\eta_{COMB} = 100\%$
Ambient	**Compresseur**	**Turbine**
$T_{amb} = 288$ K $P_{amb} = 101.3$ kPa	$PR_{COMP} = 3.25$ $\eta_{COMP} = 81.35\%$	$T_{04} = 1175$ K $\eta_{HPT} = 83.75\%$ $\eta_{PT} = 92.25\%$
		Nozzle
	$SFC = \frac{f}{\sum \Delta h}$	$\eta_{nozzzle} = 100\%$

Simplified Performance Calculation

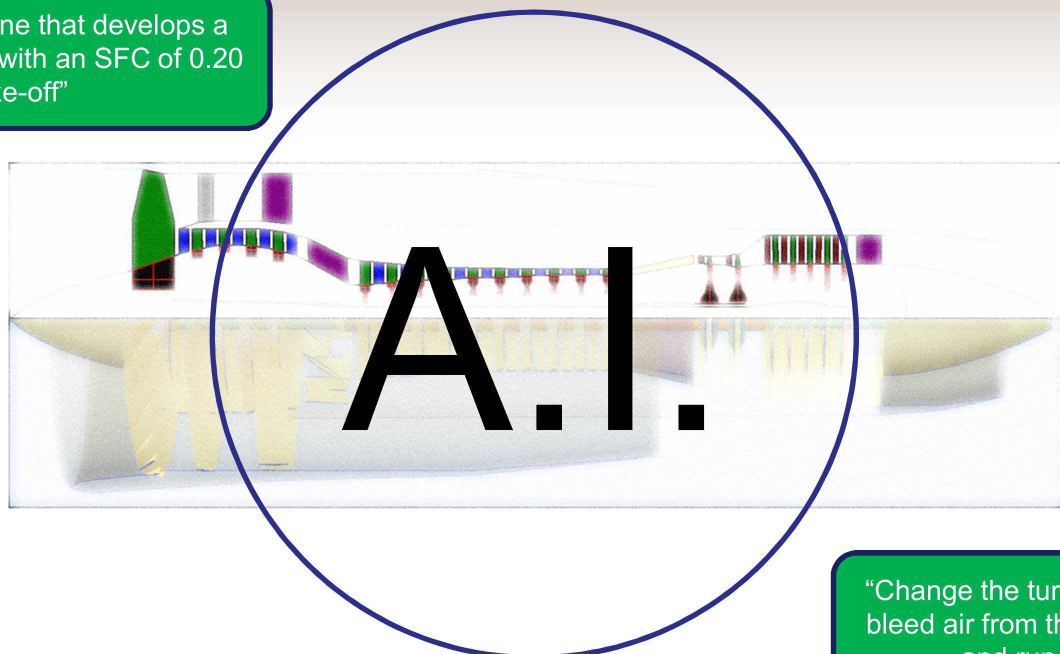
Intake	$T_{T2}/T_{T0}=1$ $0.4<\mathrm{K}<0.7$	$\eta_{INLET}=P_{T2}/P_{T1}$ $\eta_{RAM}=\frac{P_{T2}-P_{S1}}{P_{T1}-P_{S1}}$ $D_{SPILL}=K\cdot[\dot m_1(V_{abs1}-V_{abs0})+A_1(P_{S1}-P_{S0})]$
Compressor	$H=\dot mC_p\Delta T_{T23}=\dot mC_p(T_{T2}-T_{T3})$	$\eta_C=\frac{T_{T2}}{\Delta T_{T23}}\left[PR_{32}^{(\gamma-1)/\gamma}-1\right]=\frac{T_{T2}}{(T_{T3}-T_{T2})}\left[\left(\frac{P_{T3}}{P_{T2}}\right)^{(\gamma-1)/\gamma}-1\right]$
Combustion	$\frac{T_{T4}}{T_{T3}}=\frac{\left(1+f\cdot\eta_{COMB}\cdot\frac{Q}{(C_pT_{T3})}\right)}{(1+f)}$	-
Turbine	$H=\dot mC_p\Delta T_{T45}=\dot mC_p(T_{T4}-T_{T5})$	$\eta_T=\frac{\Delta T_{T45}}{T_{T4}\left[1-\left(\frac{1}{PR_{45}}\right)^{(\gamma-1)/\gamma}\right]}=\frac{(T_{T4}-T_{T5})}{T_{T4}\left[1-\left(\frac{1}{P_{T4}/P_{T5}}\right)^{(\gamma)-1/\gamma}\right]}$
Exhaust	$T_{T8}/T_{T5}=1$ $NPR=P_{T8}/P_{S8}=P_{T8}/P_{S0}$ $V_{abs8}=\sqrt{2\cdot\eta_{NOZZLE}\cdot C_P\cdot T_{T8}\left[1-\left(\frac{1}{NPR}\right)^{\gamma-1/\gamma}\right]}$	$\eta_{NOZZLE}=\frac{T_{T5}-T_{S8}}{T_{T5}\left[1-\left(\frac{P_{S8}}{P_{T5}}\right)^{\gamma-1/\gamma}\right]}$
Mechanical or Parasitic Loss	$WORK_{COMP}=\frac{1}{\eta_m}C_p\cdot\Delta T_{32}$	$\frac{1}{\eta_{para}}$
Thrust	$Thrust=(1+f)\cdot(\dot m_{IN}-\dot m_{BLEED})V_{EX}-\dot m_{IN}V_{IN}+A_{EX}(P_{EX}-P_{IN})$	$V_{EX}=V_{abs8}=\sqrt{2\cdot\eta_{NOZZLE}\cdot C_P\cdot T_{T8}\left[1-\left(\frac{1}{NPR}\right)^{\gamma-1/\gamma}\right]}$

Goal of the future

TWO MAIN GOALS

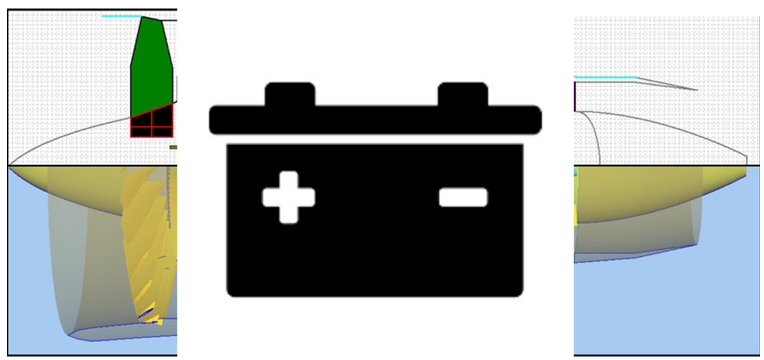
"Hey Google …"

"I need a gas turbine that develops a thrust of 63,500 lbf with an SFC of 0.20 at take-off"



"Change the turbine disk material, use bleed air from the stator leading edge, and run full 3D please"

Or …



Any questions?