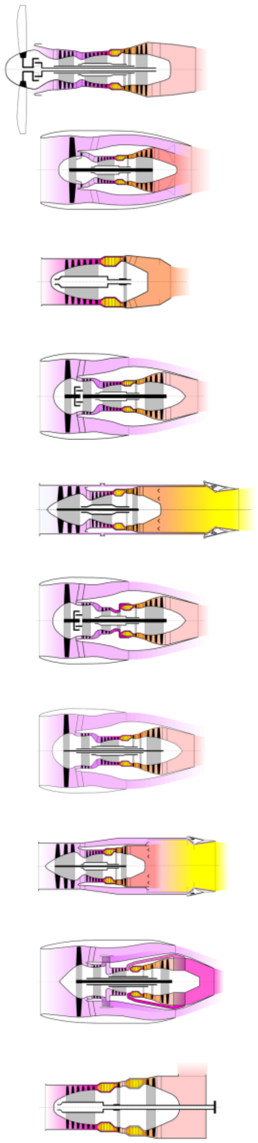

Simulation of Starting and Windmilling

A tutorial by Joachim Kurzke

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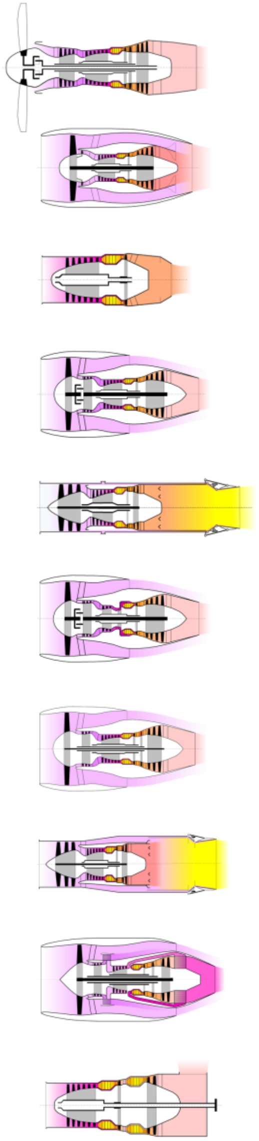
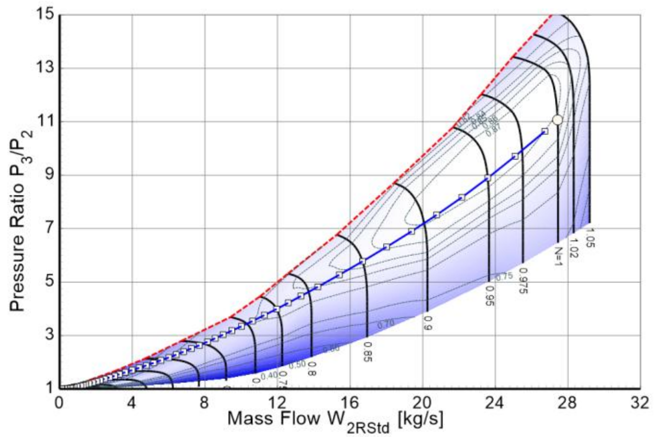


Preface

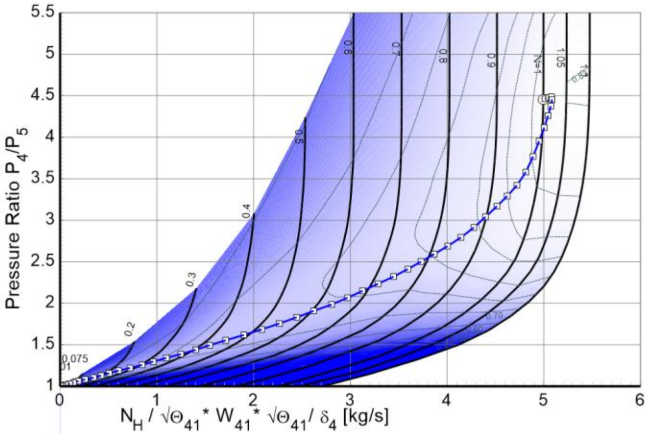
It is a widespread view that reasonably accurate gas turbine performance calculations are only feasible between idle and max power.

However, the common performance programs can calculate the thermodynamic cycle for spool speeds as low as 1% of the design value provided physically sound compressor and turbine maps are available.

The 2nd edition of the book "Propulsion and Power" describes how to extend compressor and turbine maps from the idle region down to extremely low spool speeds. With such maps it is feasible to simulate engine starting and windmilling.



Gas generator operating lines



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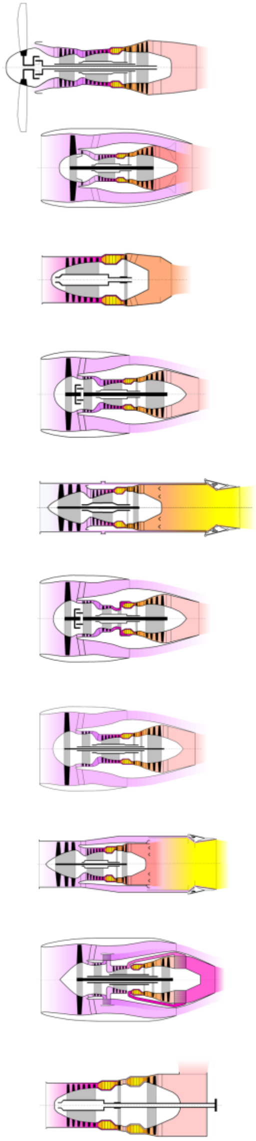

Outline

This tutorial is intended to support readers of Chapter 17 in "Propulsion and Power" who want to carry out their own calculations on starting and windmilling.

The first part of the tutorial describes the steps involved in simulating the start-up of an aircraft engine. Although the specific algorithms in your favorite performance program may differ, the underlying principles remain the same as described here.

The presented example simulation is supplemented by sensitivity studies, which illustrate the importance of the various input data.

The second part of this tutorial is dedicated to the simulation of windmilling. It also covers relighting an engine from the windmilling state.

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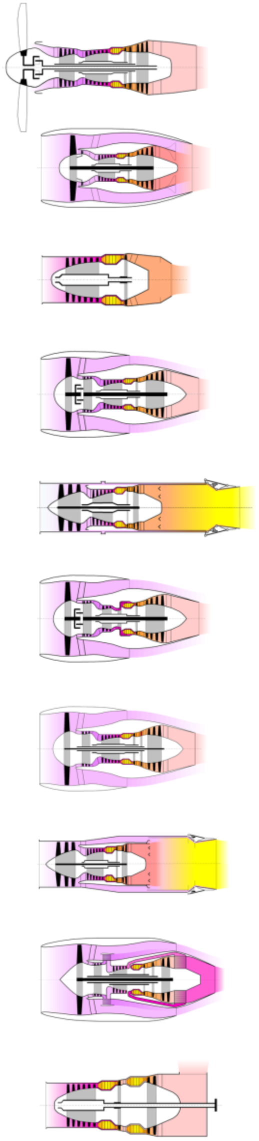
Preparing an Engine Start Simulation



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1 Create an engine model consisting of

- The thermodynamic cycle design point
- Extended compressor and turbine maps
  - downto very low speed (10% … 1%)
- Engine geometry description (yields a guess of rotor inertia)

2 Check the thermodynamic model

- Intake pressure ratio = 1 at zero spool speed?
- Customer Bleed = 0 kg/s at zero spool speed?
- There must not be losses which do not decrease with spool speed!

3 Search for a suitable point to initialize the simulation

- Zero spool speed is trivial, but no cycle calculation feasible
- A crank point at very low spool speed is required
  - run a 30% spool speed case with fuel
  - switch to crank mode
  - run an operating line in crank mode down to minimum simulatable spool speed

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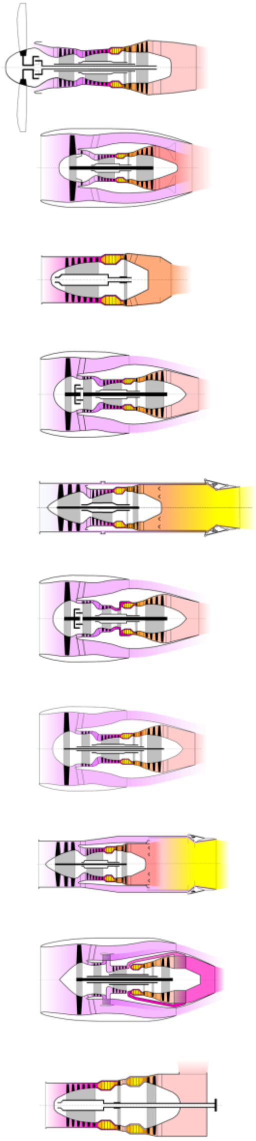
Cycle Design Point

Gas Generator Model of the CFM56-3



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SL static, ISA

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		288.15	101.325	
1	27.436	288.15	101.325	
2	27.436	288.15	101.325	27.436
3	27.436	609.27	1121.668	3.604
31	23.568	609.27	1121.668	
4	23.973	1228.40	1065.584	4.707
41	25.894	1185.80	1065.584	4.995
49	25.894	886.65	239.176	
5	27.540	870.78	239.176	20.282
6	27.540	870.78	239.176	
8	27.540	870.78	239.176	20.282
Bleed	0.302	609.27	1121.668	

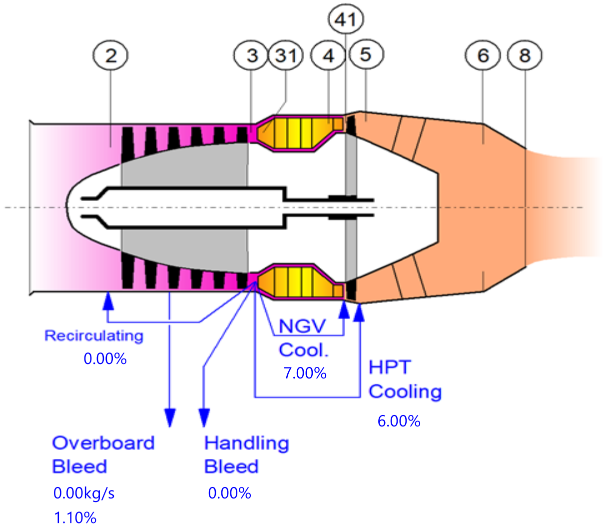
P2/P1 = 1.0000   P4/P3 = 0.9500   P6/P5 1.0000

Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0.8677	0.9033	1.000	11.070
Burner	0.9995			0.950
Turbine	0.8250	0.7960	2.003	4.455

Spool mech Eff 0.9900   Nom Spd 13498 rpm

hum [%]	war0	FHV	Fuel
0.0	0.00000	42.769	Generic

		Value	Unit	Cycle Design Point
FN	=	17.08	kN	Net Thrust
TSFC	=	23.7534	g/(kN*s)	Thrust Specific Fuel Consumption
FN/W2	=	622.66	m/s	Specific Thrust
Prop Eff	=	0.0000		Propulsion Efficiency
eta core	=	0.3060		Core Efficiency
WF	=	0.40579	kg/s	Fuel Flow
s NOx	=	0.24987		NOx Severity Parameter
XM8	=	1.0000		Nozzle Throat Mach No.
A8	=	0.0854	m²	Geometric Nozzle Throat Area
P8/Pamb	=	2.3605		Nozzle Pressure Ratio
WBld/W2	=	0.01100		Bleed Air Flow/Mass Flow W2
Ang8	=	1.00	deg	Nozzle Petal Angle
CD8	=	0.9980		Nozzle Discharge Coefficient
WClN/W2	=	0.07000		Turbine Nozzle Guide Vane Cooling Air / W2
WClR/W2	=	0.06000		Turbine Rotor Cooling Air/ W2
Loading	=	100.00	%	Burner Loading in % of the Cycle Design Point Value
e45 th	=	0.79974		Thermodynamic Turbine Efficiency
far8	=	0.01495		Nozzle Throat Fuel-Air-Ratio
PWX	=	0.00	kW	Power Offtake



Ref.
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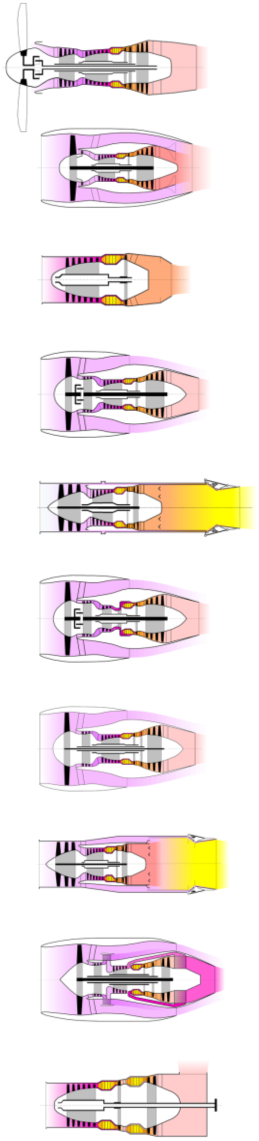

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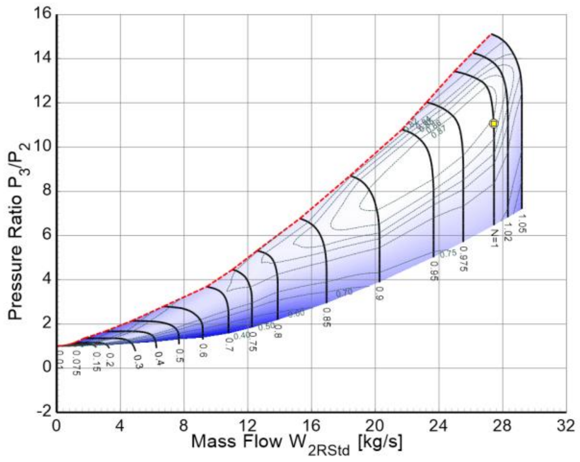
Extended Maps



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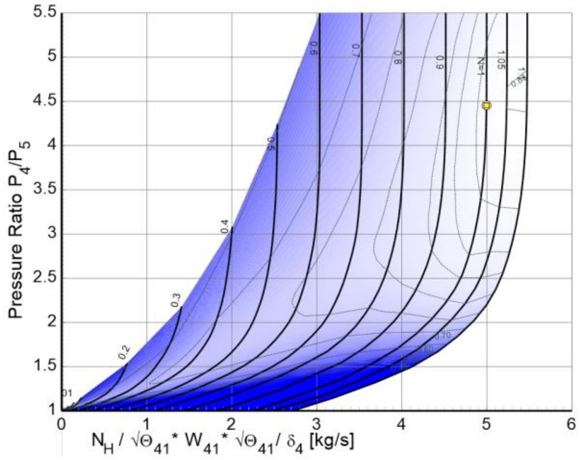
ISABE2007_1184_Fig29_ExtndGasTurb.txt

Save as

ISABE2007_1184_Fig29_ExtndGasTurb.Map

- Set the map scaling point to N=1, ß=0.5



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NASATM83655_ExtndTurbine.txt

Save as

NASATM83655_ExtndTurbine.Map

- Set the map scaling point to N=1, ß=0.5

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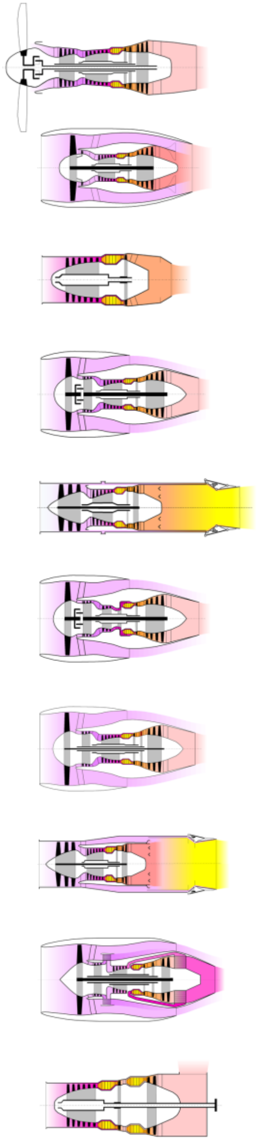

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Steady State Operation
30% Spool Speed

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		288.15	101.325	
1	2.313	288.15	101.325	
2	2.313	288.15	101.325	2.313
3	2.313	337.54	136.838	1.853
31	1.987	337.54	136.838	
4	2.027	1087.70	135.028	2.955
41	2.189	1037.21	135.028	3.116
49	2.189	992.25	102.390	
5	2.327	956.36	102.390	4.196
6	2.327	956.36	102.390	
8	2.327	956.36	102.390	4.196
Bleed	0.025	337.54	136.838	

P2/P1 = 1.0000 P4/P3 = 0.9868 P6/P5 1.0000

Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0.5217	0.5415	1.000	1.350
Burner	0.9826			0.987
Turbine	0.6663	0.6588	0.296	1.319

Spool mech Eff 0.9900 Speed 30.00 %

hum [%]	war0	FHV	Fuel
0.0	0.00000	42.769	Generic

SL static, ISA , Rel GG Speed=0.300

FN	=	0.18	kN	Net Thrust
TSFC	=	227.3385	g/(kN*s)	Thrust Specific Fuel Consumption
FN/W2	=	76.22	m/s	Specific Thrust
Prop Eff	=	0.0000		Propulsion Efficiency
eta core	=	0.0039		Core Efficiency
P5/P2	=	1.0105	EPR	Engine Pressure Ratio
WF	=	0.04007	kg/s	Fuel Flow
s NOx	=	0.02662		NOx Severity Parameter
XM8	=	0.1256		Nozzle Throat Mach No.
A8	=	0.0881	m²	Geometric Nozzle Throat Area
P8/Pamb	=	1.0105		Nozzle Pressure Ratio
WBld/W2	=	0.01100		Bleed Air Flow/Mass Flow W2
Ang8	=	16.00	deg	Nozzle Petal Angle
CD8	=	0.9427		Nozzle Discharge Coefficient
WClN/W2	=	0.07000		Turbine Nozzle Guide Vane Cooling Air / W2
WClR/W2	=	0.06000		Turbine Rotor Cooling Air/ W2
Loading	=	919.88	%	Burner Loading in % of the Cycle Design Point Value
e45 th	=	0.65477		Thermodynamic Turbine Efficiency
far8	=	0.01752		Nozzle Throat Fuel-Air-Ratio
PWX	=	0.00	kW	Power Offtake

Standard off-design iteration setup for a given speed

Variable	Error
Beta in HPC Map	*Turbine Flow*
T4	*Turbine Pressure Ratio*
Beta in HPT Map	*Nozzle Pressure Ratio*

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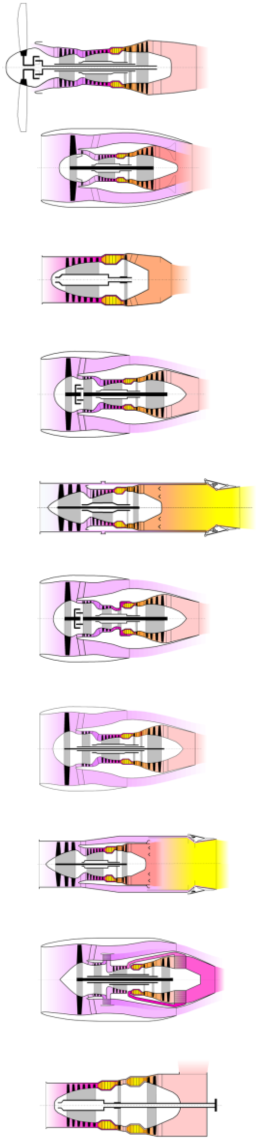
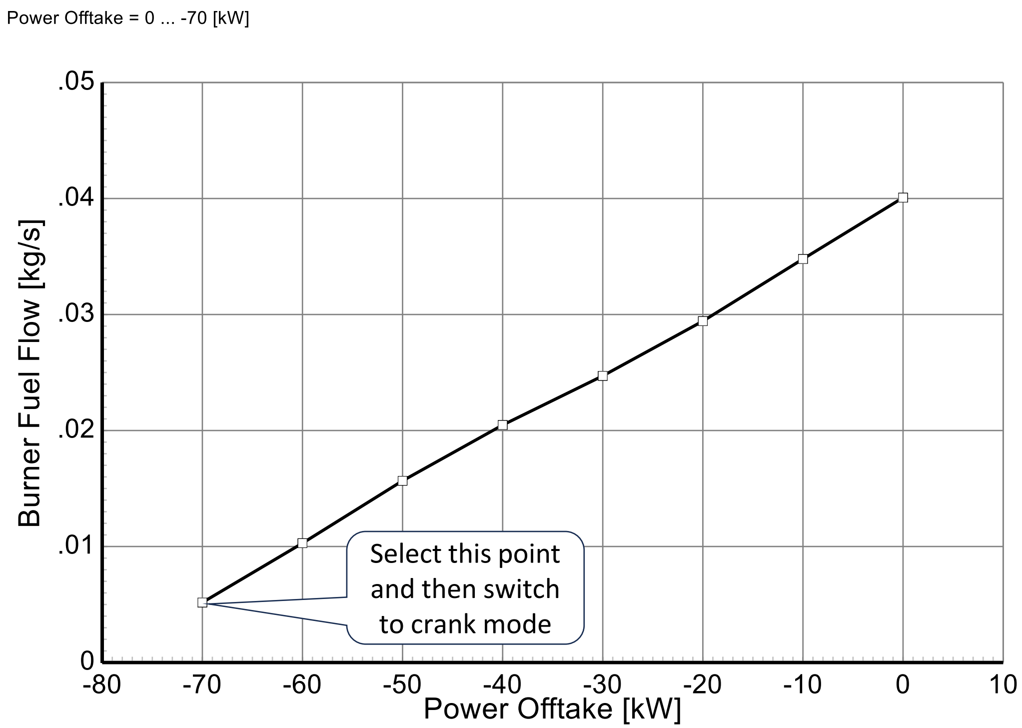


Parametric Study With Negative PWX



One might encounter convergence problems when switching from a normal steady-state performance point with a given spool speed (fuel flow>0) to a crank point (fuel flow=0).

In such a case, run a parametric study with decreasing power offtake. Select a point with low fuel flow from this study, and then switch to crank mode.

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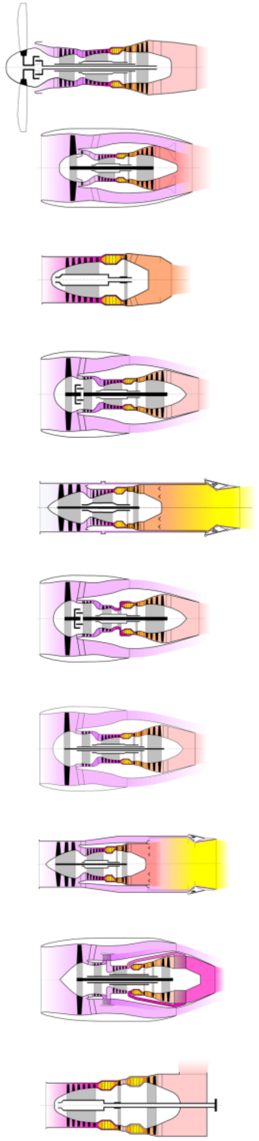

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Steady State Operation
30% Spool Speed, No Fuel - Crank

```
          W          T          P          WRstd       SL static, ISA ,  Rel GG Speed=0.300,  crank
Station  kg/s        K         kPa         kg/s
 amb               288.15    101.325                   FN        =      0.10 kN          Net Thrust
  1      3.867     288.15    101.325                   TSFC      =    0.0000 g/(kN*s)    Thrust Specific Fuel Consumption
  2      3.867     288.15    101.325      3.867        FN/W2     =     24.84 m/s         Specific Thrust
  3      3.867     320.63    136.133      3.036
 31      3.322     320.63    136.133                   Prop Eff =    0.0000              Propulsion Efficiency
  4      3.322     320.63    131.302      2.704        eta core =    0.0000              Core Efficiency
 41      3.593     320.63    131.302      2.925        P5/P2     =    1.0036 EPR         Engine Pressure Ratio
 49      3.593     307.68    101.686                   WF        =   0.00000 kg/s        Fuel Flow
  5      3.825     308.47    101.686      3.943        s NOx     =   0.00000             NOx Severity Parameter
  6      3.825     308.47    101.686                   XM8       =    0.0714             Nozzle Throat Mach No.
  8      3.825     308.47    101.686      3.943        A8        =    0.0881 m²          Geometric Nozzle Throat Area
Bleed    0.043     320.63    136.133                   P8/Pamb   =    1.0036             Nozzle Pressure Ratio
--------------------------------------------           WBld/W2   =   0.01100             Bleed Air Flow/Mass Flow W2
P2/P1 = 1.0000   P4/P3 = 0.9645   P6/P5 1.0000         Ang8      =     16.00 deg         Nozzle Petal Angle
Efficiencies:    isentr   polytr    RNI    P/P         CD8       =    0.9783             Nozzle Discharge Coefficient
 Compressor      0.7797   0.7887   1.000   1.344       WClN/W2   =   0.07000             Turbine Nozzle Guide Vane Cooling Air / W2
 Burner          0.0000                    0.965       WClR/W2   =   0.06000             Turbine Rotor Cooling Air/ W2
 Turbine         0.5752   0.5662   1.141   1.291       Loading   =    919.88 %           Burner Loading in % of the Cycle Design Point Value
--------------------------------------------           e45 th    =   0.00000             Thermodynamic Turbine Efficiency
Spool mech Eff   0.9900   Speed         30.00 %        far8      =   0.00000             Nozzle Throat Fuel-Air-Ratio
--------------------------------------------           PWX       =    -79.99 kW          Power Offtake
 hum [%]      war0       FHV      Fuel
```

Crank iteration setup, spool speed is given	
Variable	Error
Beta in HPC Map	*Turbine Flow*
PWX	*Turbine Pressure Ratio*
Beta in HPT Map	*Nozzle Pressure Ratio*

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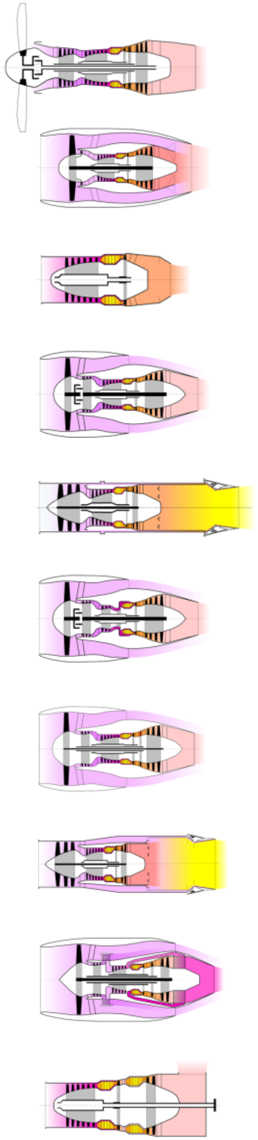
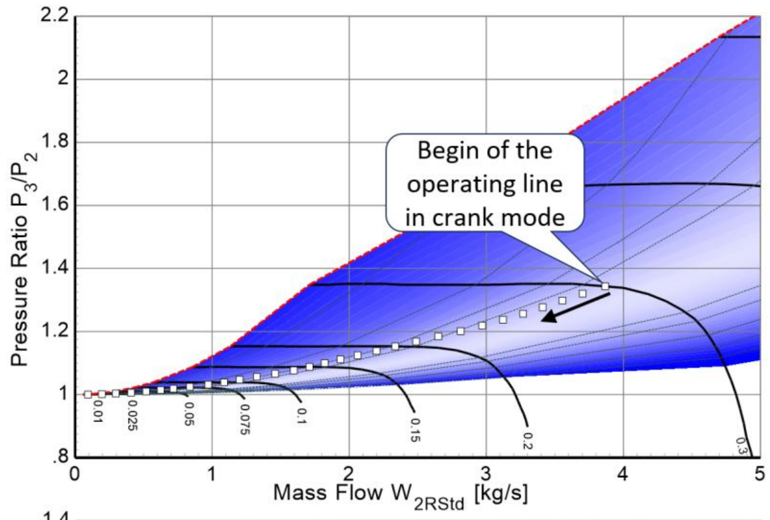
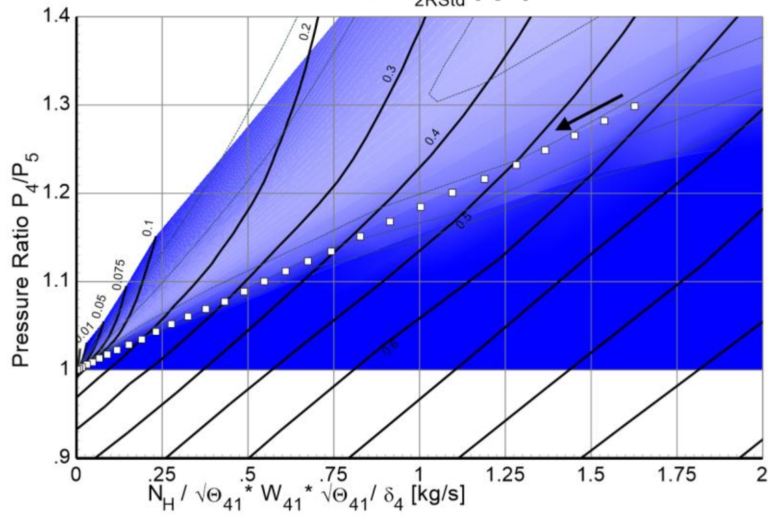
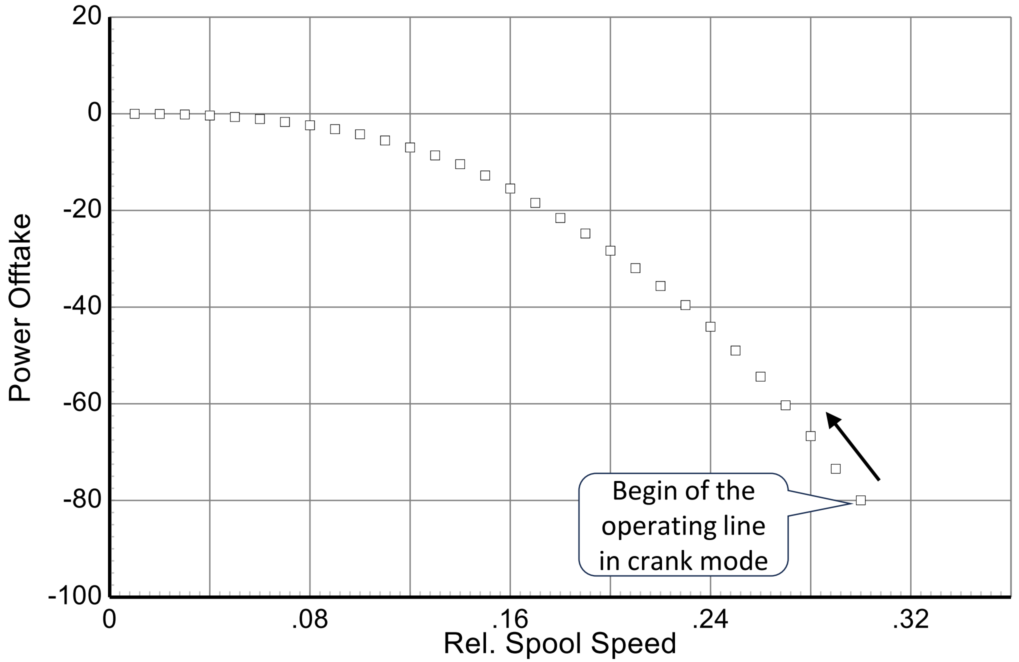


Operating Points in Crank Mode
From 30% Spool Speed Downto 1%







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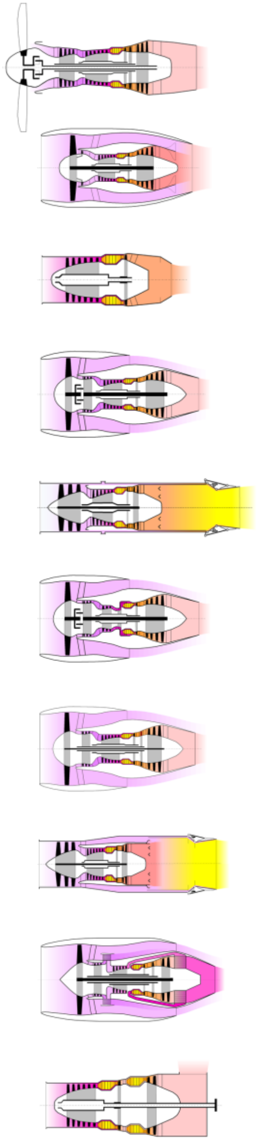

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Crank - 1% Spool Speed
Begin of the Engine Start Simulation

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		288.15	101.325	
1	0.094	288.15	101.325	
2	0.094	288.15	101.325	0.094
3	0.094	288.20	101.364	0.094
31	0.081	288.20	101.364	
4	0.081	288.20	101.361	0.081
41	0.087	288.20	101.361	0.087
49	0.087	288.25	101.326	
5	0.093	288.24	101.326	0.093
6	0.093	288.24	101.326	
8	0.093	288.24	101.326	0.093
Bleed	0.001	288.20	101.364	

P2/P1 = 1.0000 P4/P3 = 1.0000 P6/P5 1.0000

Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0.5964	0.5953	1.000	1.000
Burner	0.0000			1.000
Turbine	-1.5059	-1.5061	1.000	1.000

Spool mech Eff 0.9900 Speed 1.00 %

hum [%]	war0	FHV	Fuel
0.0	0.00000	42.769	Generic

SL static, ISA , Rel GG Speed=0.010, crank

FN	=	9.1E-5	kN	Net Thrust
TSFC	=	0.0000	g/(kN*s)	Thrust Specific Fuel Consumption
FN/W2	=	0.97	m/s	Specific Thrust
Prop Eff	=	0.0000		Propulsion Efficiency
eta core	=	0.0000		Core Efficiency
P5/P2	=	1.0000	EPR	Engine Pressure Ratio
WF	=	0.00000	kg/s	Fuel Flow
s NOx	=	0.00000		NOx Severity Parameter
XM8	=	0.0029		Nozzle Throat Mach No.
A8	=	0.0881	m²	Geometric Nozzle Throat Area
P8/Pamb	=	1.0000		Nozzle Pressure Ratio
WBld/W2	=	0.01100		Bleed Air Flow/Mass Flow W2
Ang8	=	16.00	deg	Nozzle Petal Angle
CD8	=	0.9984		Nozzle Discharge Coefficient
WClN/W2	=	0.07000		Turbine Nozzle Guide Vane Cooling Air / W2
WClR/W2	=	0.06000		Turbine Rotor Cooling Air/ W2
Loading	=	99.99	%	Burner Loading in % of the Cycle Design Point Value
e45 th	=	0.00000		Thermodynamic Turbine Efficiency
far8	=	0.00000		Nozzle Throat Fuel-Air-Ratio
PWX	=	-0.01	kW	Power Offtake

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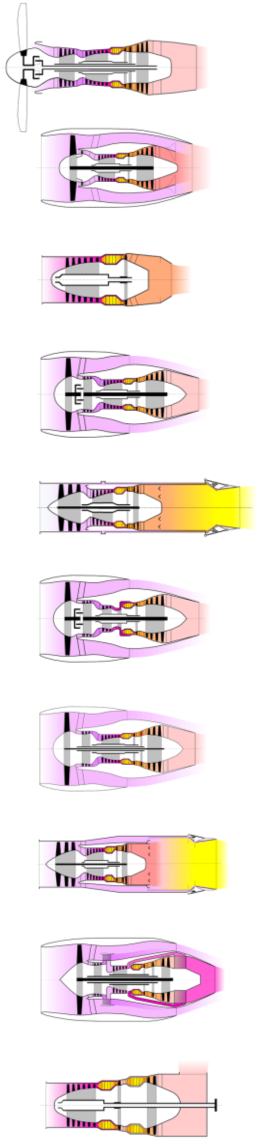

Engine Start Simulation

A Special Case of a Transient Manouver

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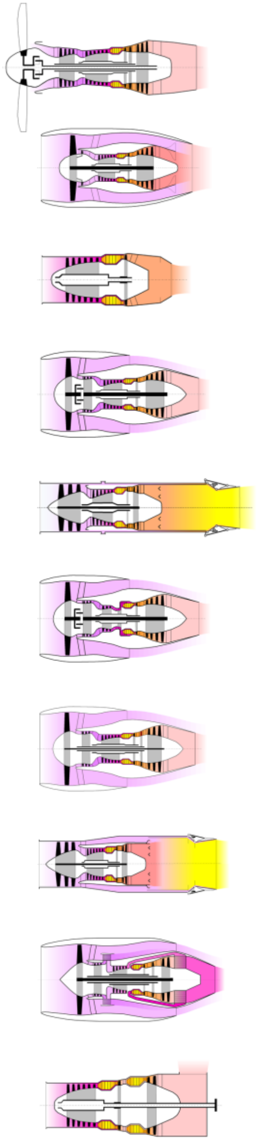

How it Works

Engine starting is a transient event that begins with a steady-state crank point at very low spool speed

Before light-up:

The starter accelerates the rotor until light-up speed is reached

- The starter is the sole source of energy during that first phase
- Starter power can be described with two numbers: torque and spool speed
- A power limit can exist

After light-up:

Both the starter and the combustion of fuel add energy to the cycle

- The amount of fuel is determined by a controller with the following limiters
  - Accel $\dot{N}/\delta$ Limit
  - Minimum fuel-air-ratio far_{min}
  - Maximum fuel-air-ratio far_{max}
  - Idle spool speed
- Fuel flow is not an input, it is a result
  - Burner efficiency varies with burner loading
  - The dubious accuracy of the burner efficiency model has only a minor impact on the overall result.

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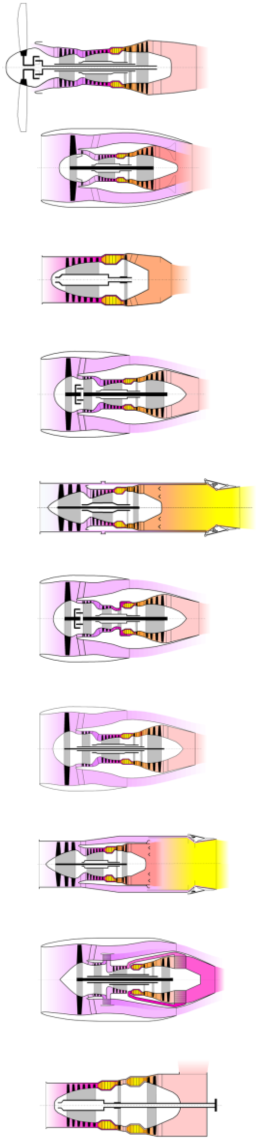
Transient Performance Simulation

Input Data for a Reference Starting Process



Rotor Inertia	kg m^2	5.69
Rel N for PLA 0% (Idle)		0.6
Proportional Control Constant		0.04
Integral Control Constant		0
Differential Control Constant		0.04
Gain Modifier		1
Minimum Fuel-Air-Ratio		0.003
Maximum Fuel-Air-Ratio		0.026
Decel (dN/dt)/(P2/Pstd) Limit		0.1
Accel (dN/dt)/(P2/Pstd) Limit		0.033
Rel. Burner Light-up Speed		0.18
Rel. Starter Cut-off Speed		0.3
Max Starter Torque	N m	150
Starter Torque Slope		-0.2
Max Starter Power	kW	40

Transient iteration setup, before light-up	
Variable	Error
Beta in HPC Map	*Turbine Flow*
PWX	*Turbine Pressure Ratio*
Beta in HPT Map	*Nozzle Pressure Ratio*

Transient iteration setup, after light-up	
Variable	Error
Acceleration Rate	*Control System*
Fuel-Air-Ratio	*Turbine Flow*
Beta in Compressor Map	*Turbine Pressure Ratio*
Beta in Turbine Map	*Nozzle Pressure Ratio*

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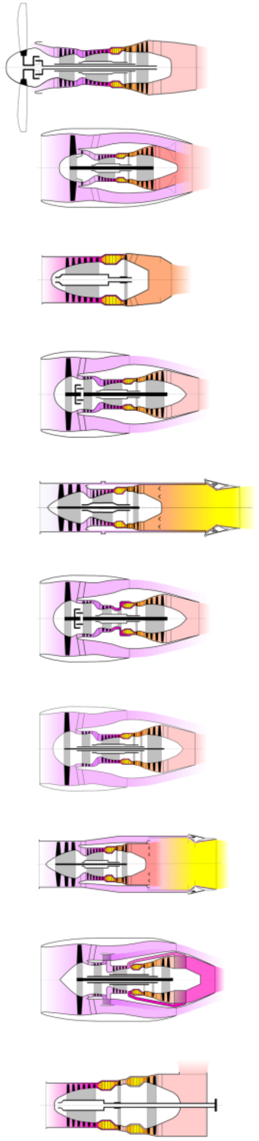

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Transient Performance Simulation After Light-up

Proportional-Integral-Differential Control

The proportional term of the speed control loop modulates the fuel flow according to

$$\Delta W_{f,P} = C_P (N_{Demand} - N)$$

while the integral term is calculated as

$$\Delta W_{f,I} = C_I \int (N_{Demand} - N)\, dt$$

Finally, the differential term is

$$\Delta W_{f,D} = C_D \frac{d(N_{Demand} - N)}{dt}$$

In a real engine, fuel flow is in principle controlled as described by these equations. In a simulation, however, it is better to control fuel flow indirectly via fuel-air-ratio because this is much less dependent on ambient conditions. Absolute fuel flow varies with engine inlet total pressure and temperature as well as spool speed, but the fuel-air-ratio is pretty much constant.

The operation of an engine model may be governed by setting selected combinations of the constants C_P (*Proportional Control Constant*), C_I *(Integral Control Constant*) and C_D (*Differential Control Constant*).

Note that the values for the control constants depend on the simulation algorithm: When fuel flow is the iteration variable, the control constants need to be adapted as engine inlet total pressure and temperature change because fuel mass flow is not a non-dimensional quantity. When fuel-air-ratio is the iteration variable, however, the control constants remain valid for a wide range of P_2 and T_2.

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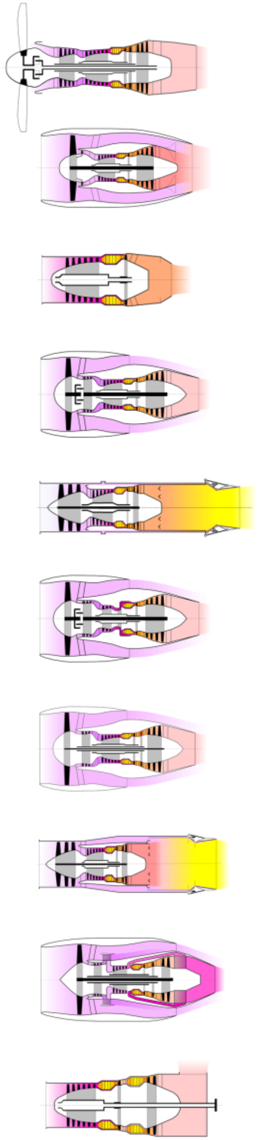
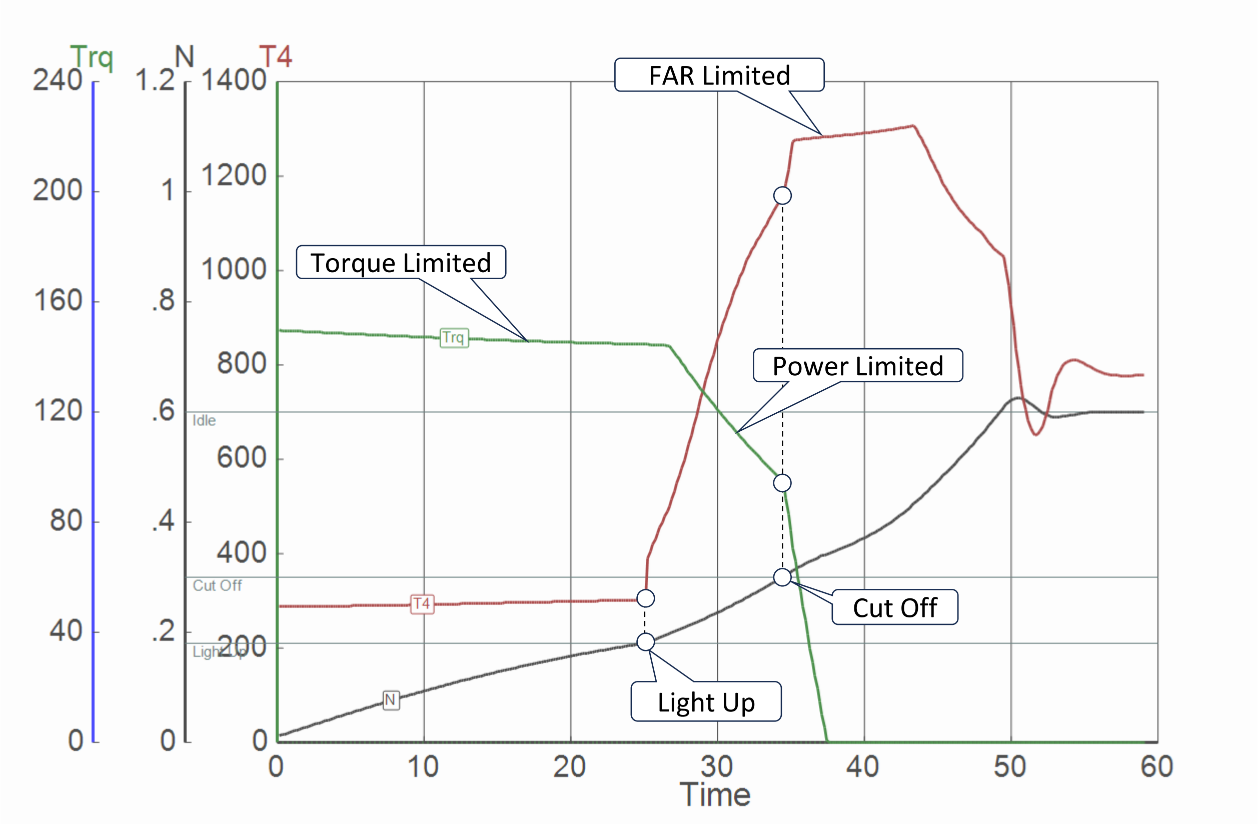


Reference Starting Process



Timestep size = 0.165 sec

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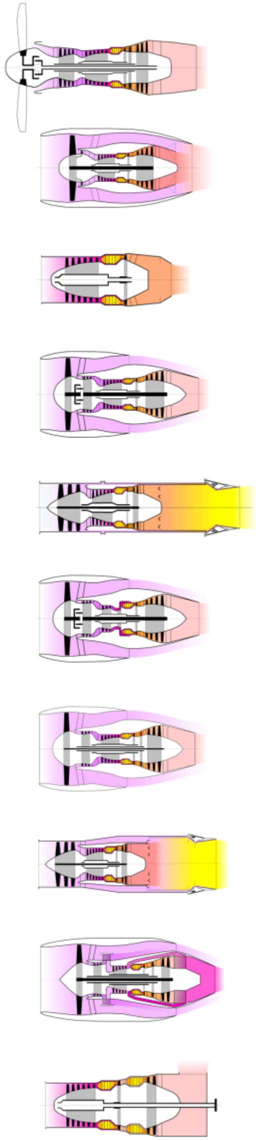

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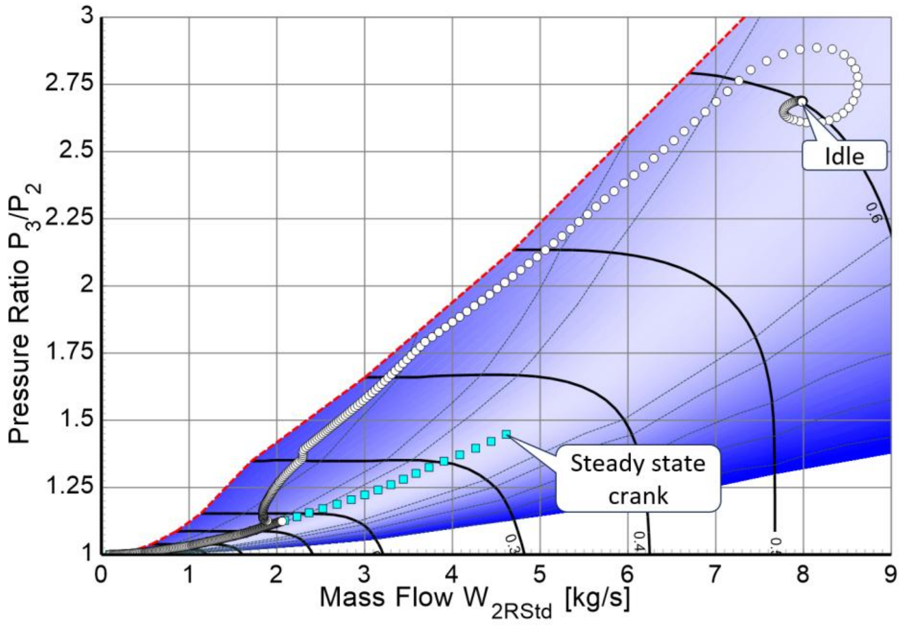
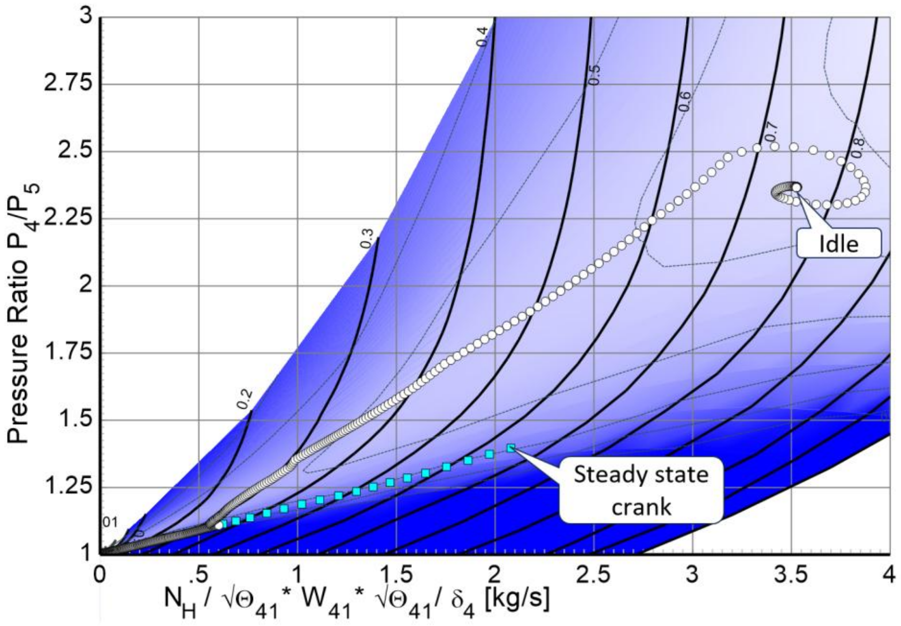
Starting in the Component Maps





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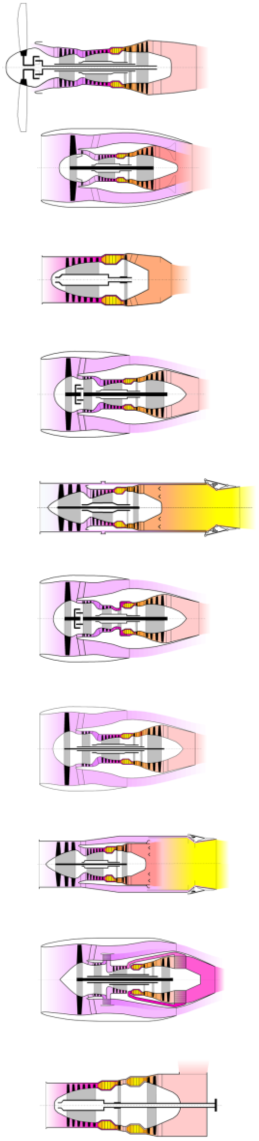

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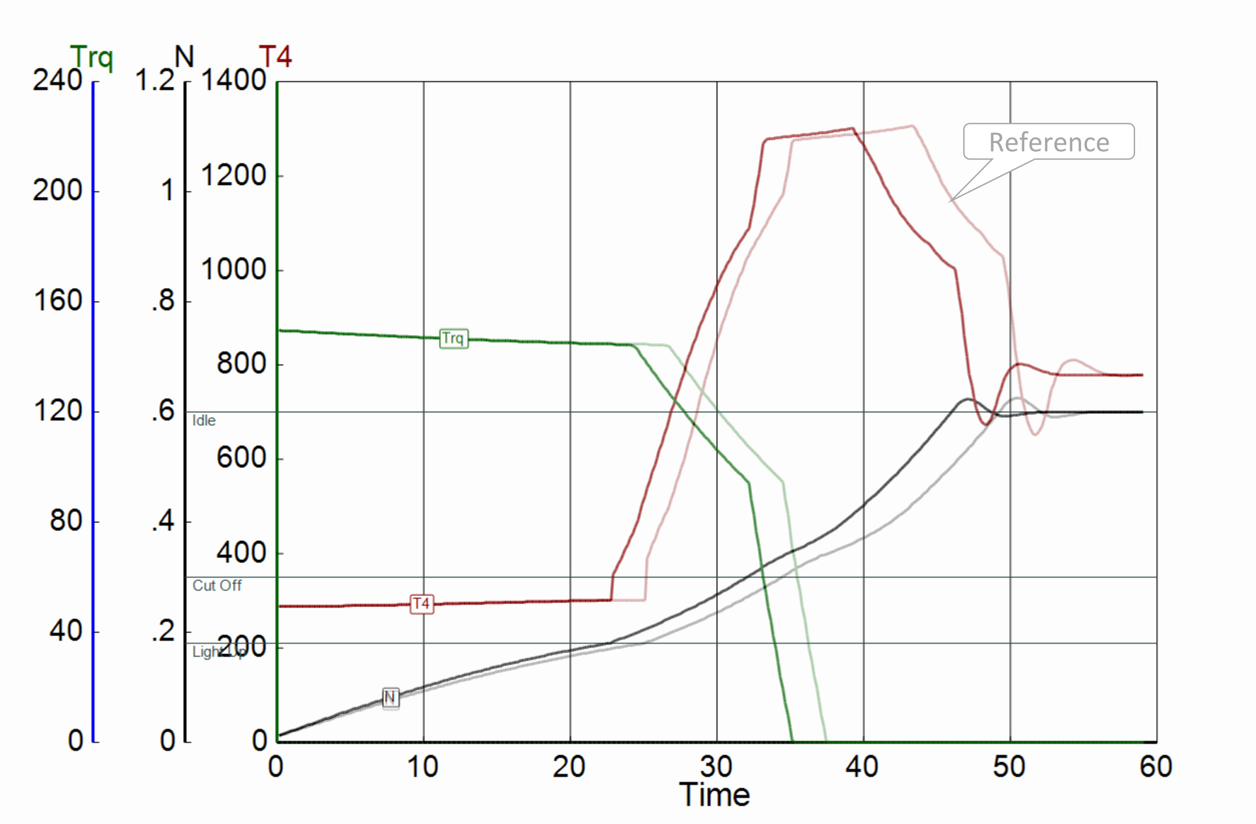
Sensitivity Studies

We will modify one input quantity at a time and compare the engine start history with our reference case.

Additionally, we demonstrate the influence of the combustion efficiency assumption on the result.

Compressor maps that extend down to 1% spool speed are rare. We also show how the simulation results are affected when the simulation begins with 10% instead of 1% spool speed.

Spool Inertia – 10%



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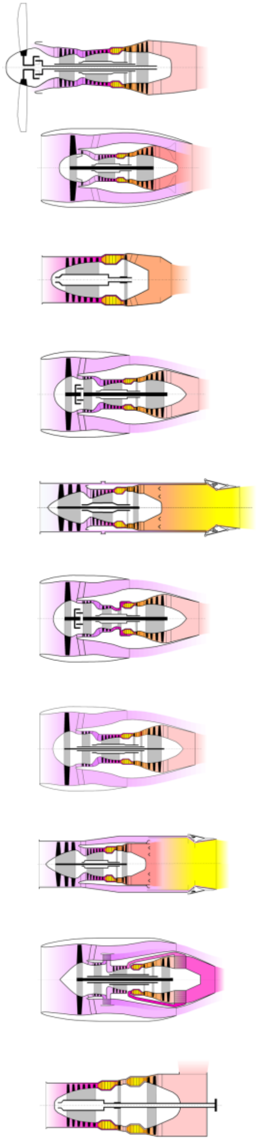

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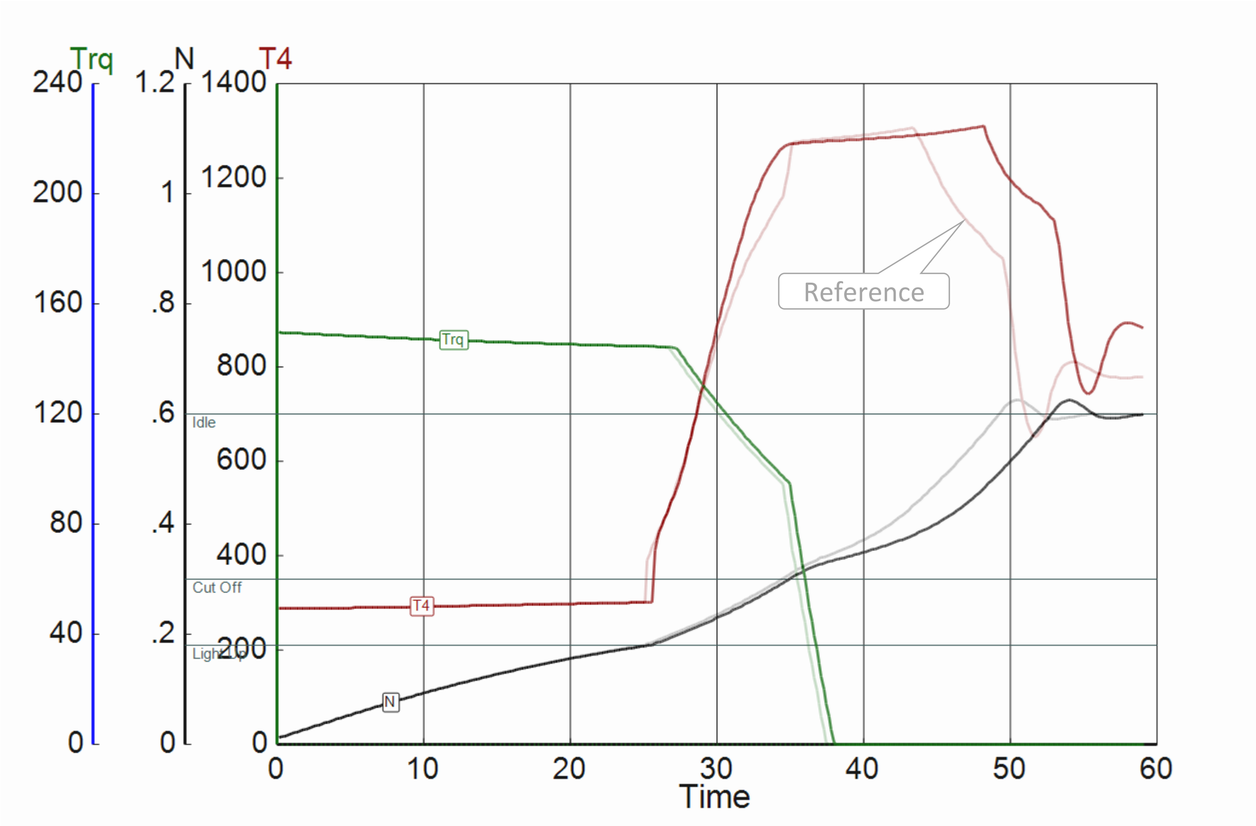
10% Handling Bleed



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Nozzle Area + 50%

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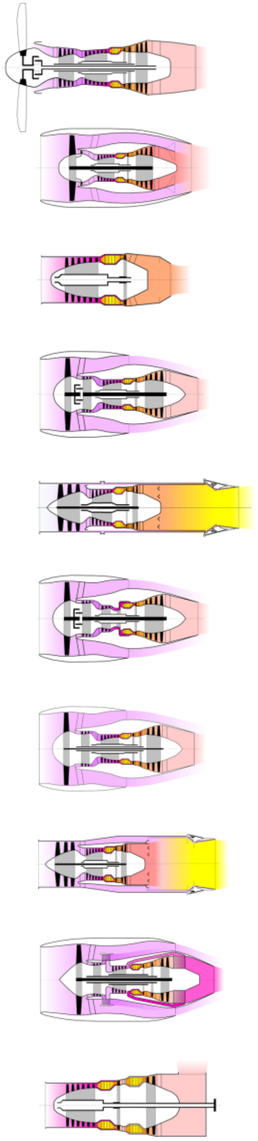

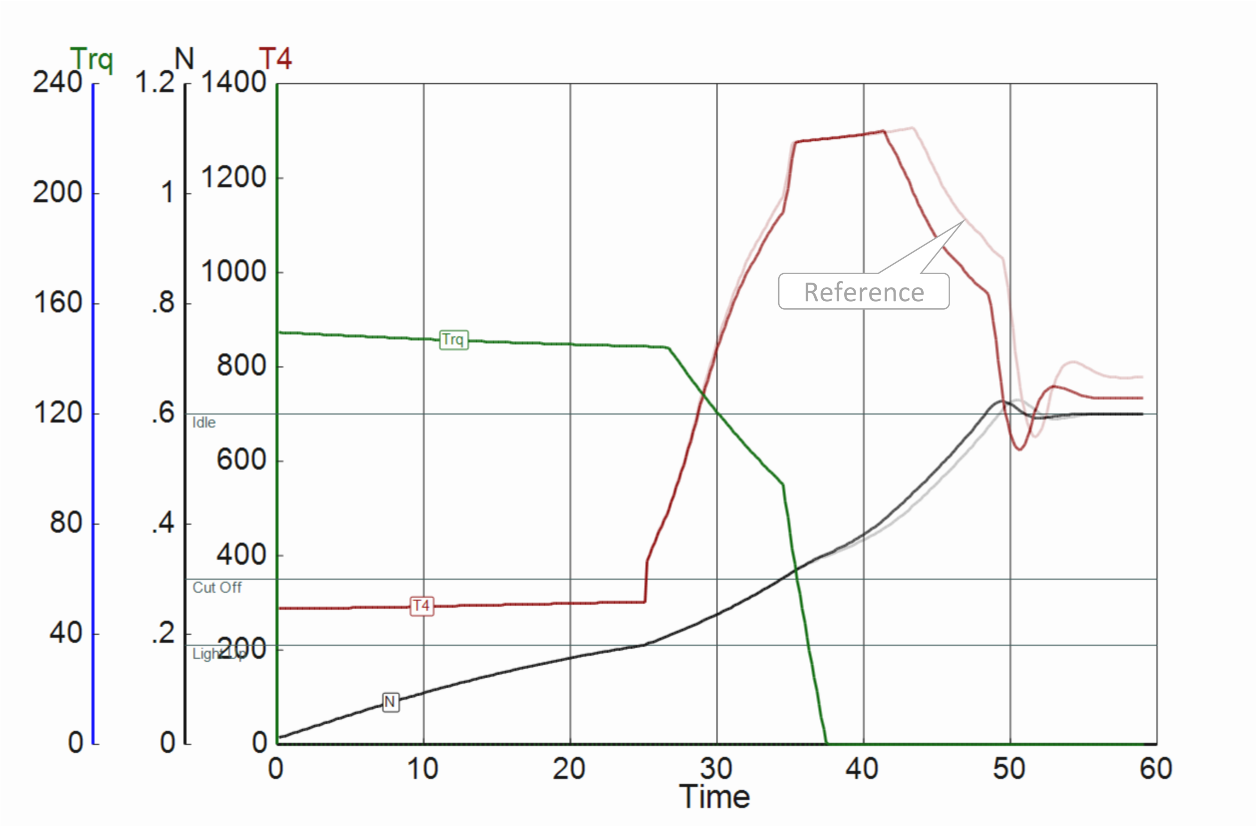

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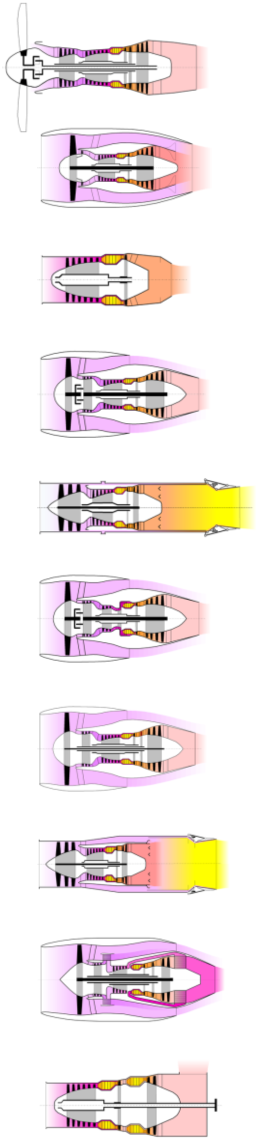
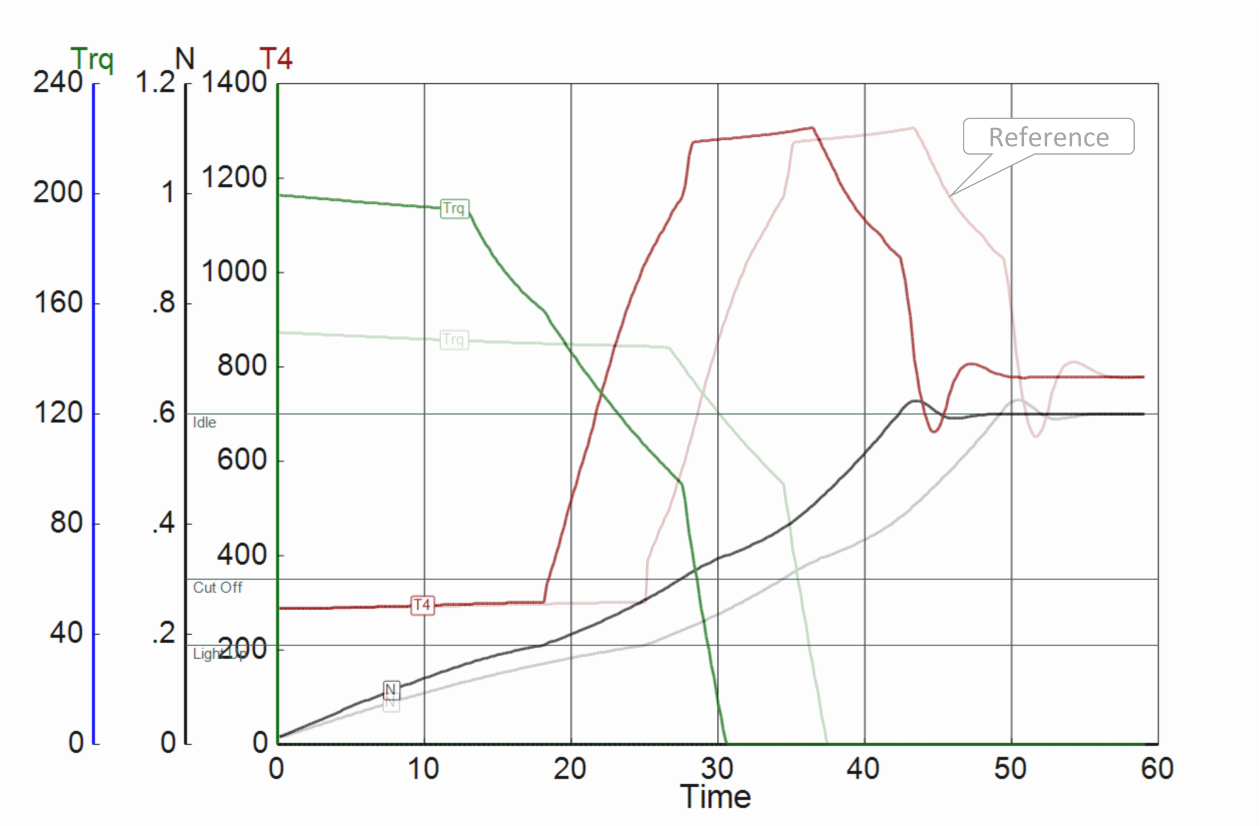


Starter Torque
From 150 to 200Nm



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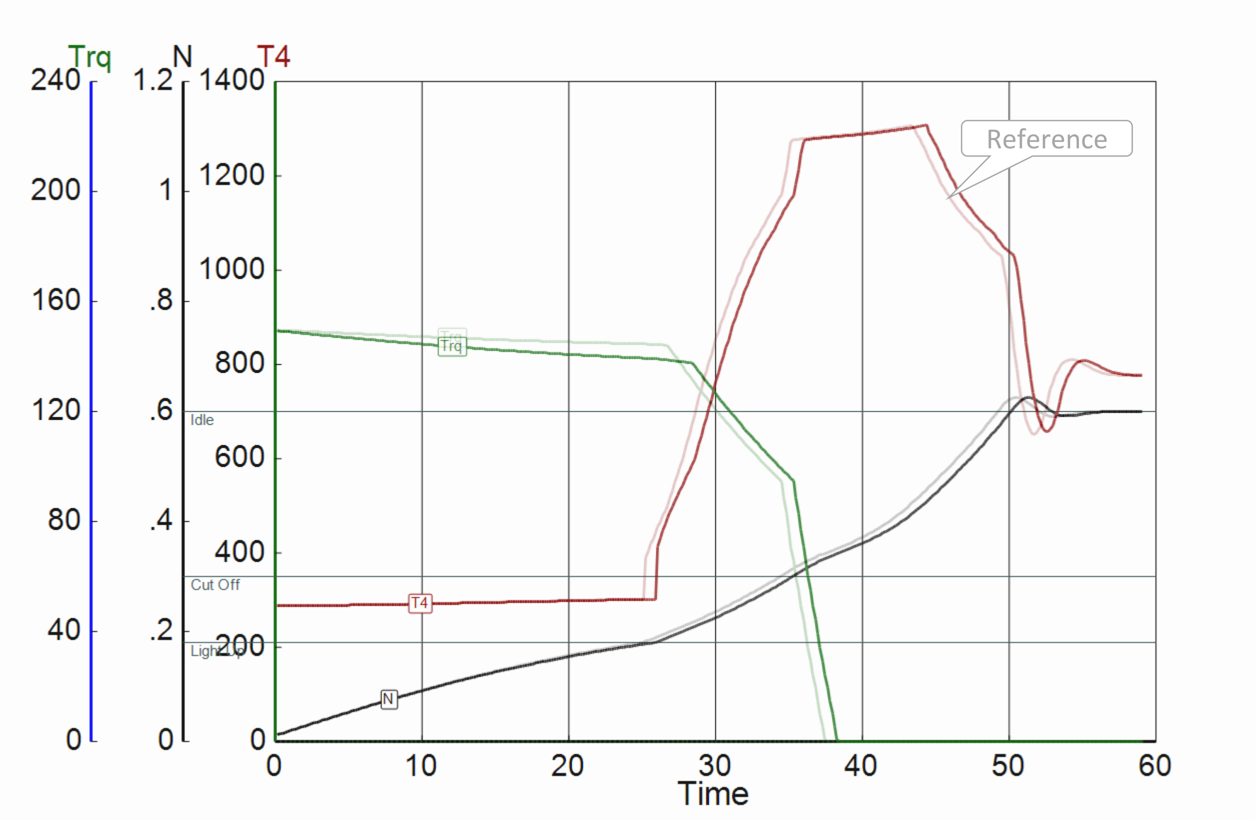
Starter Torque Slope

From -0.2 to -0.4



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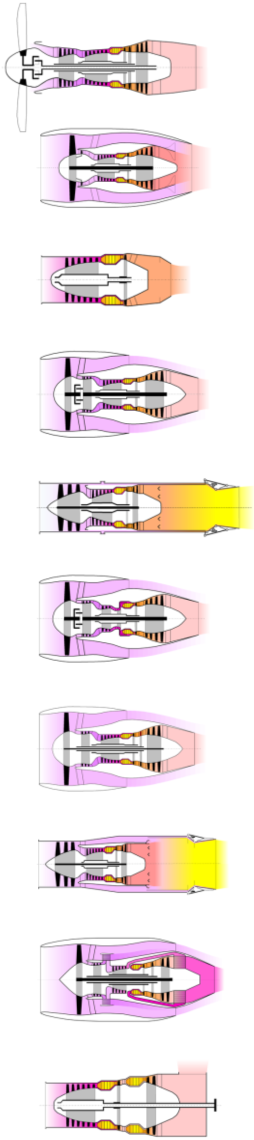
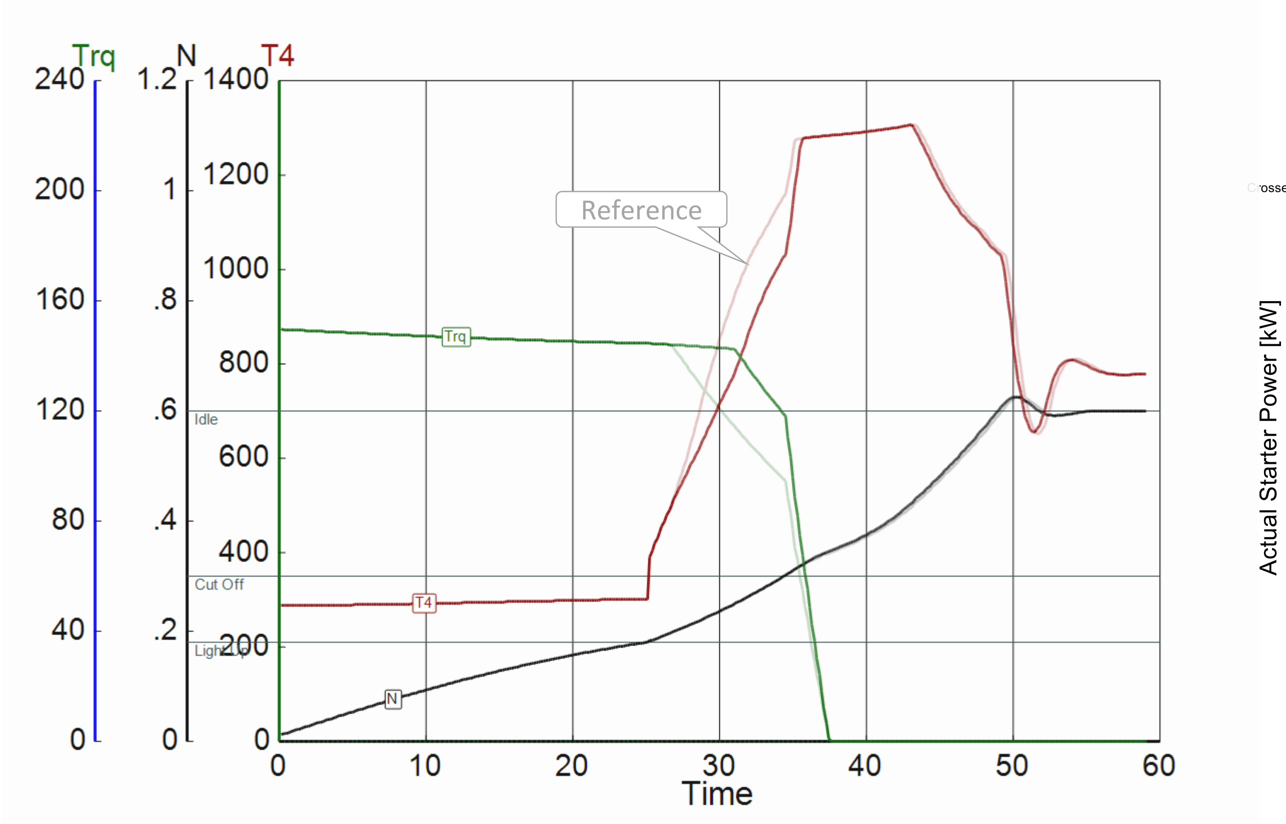
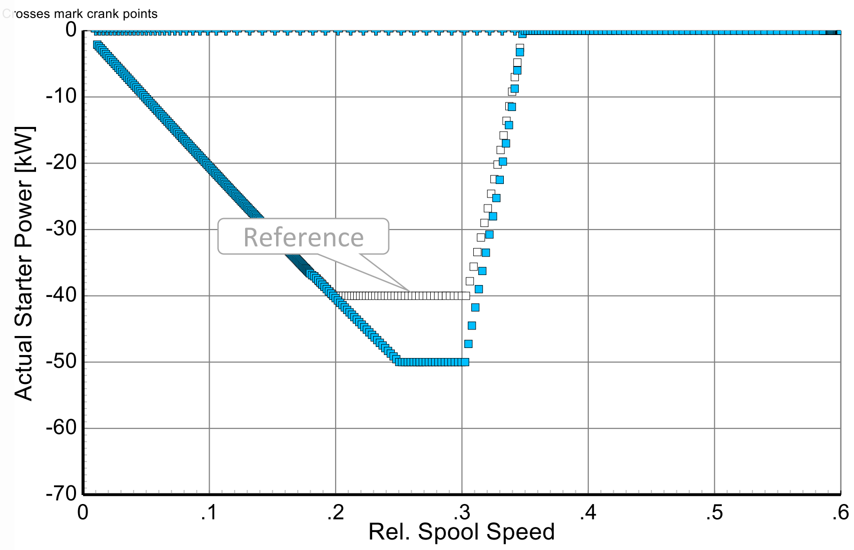


Max Starter Power
From 40 to 50kW





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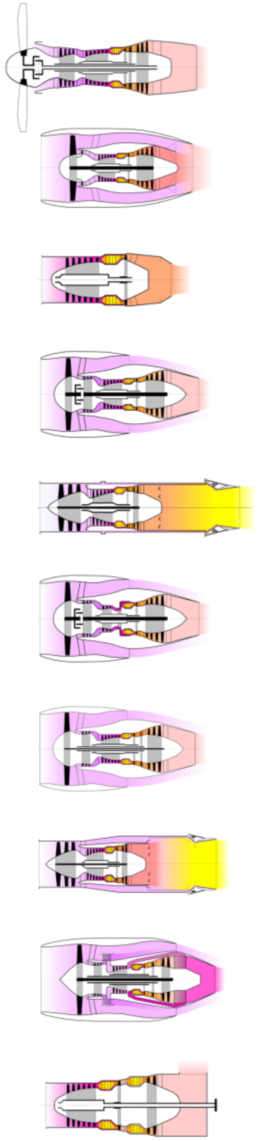
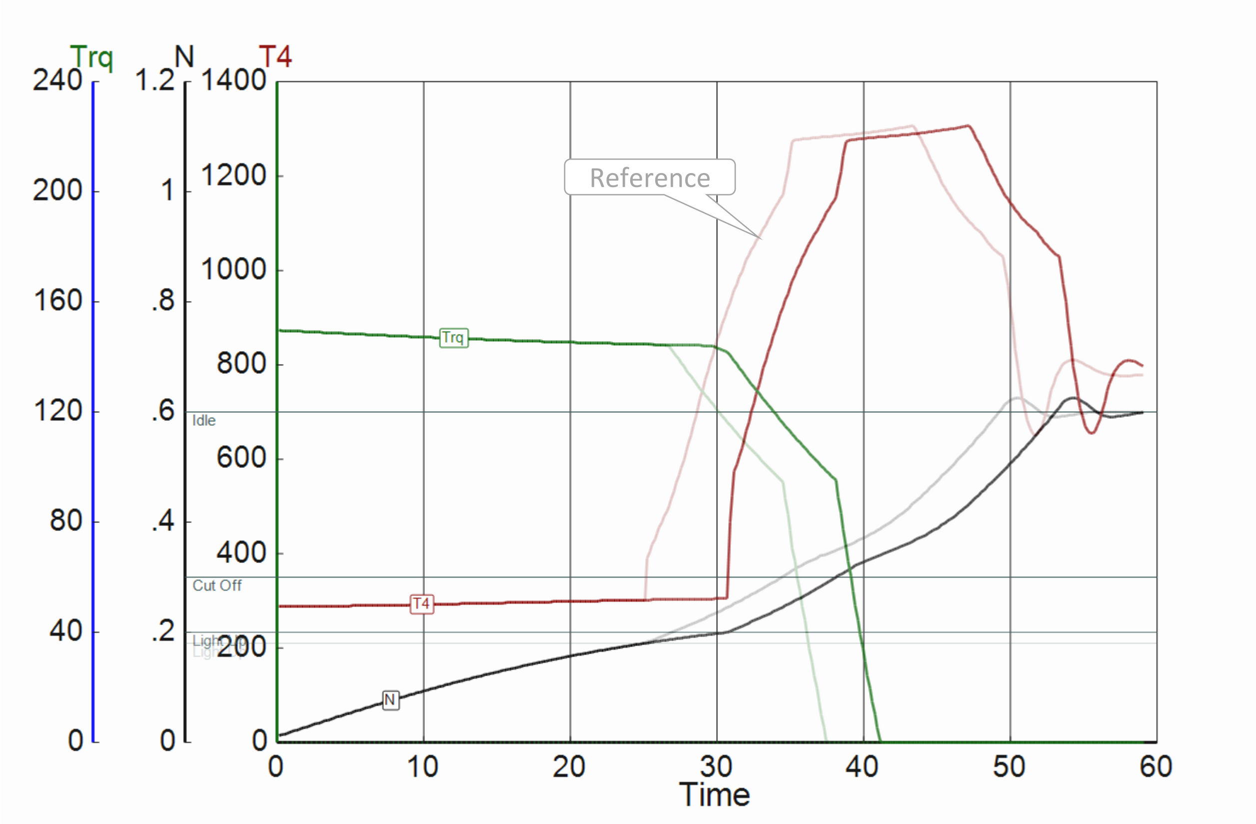
Light-up Speed

From 0.18 to 0.2





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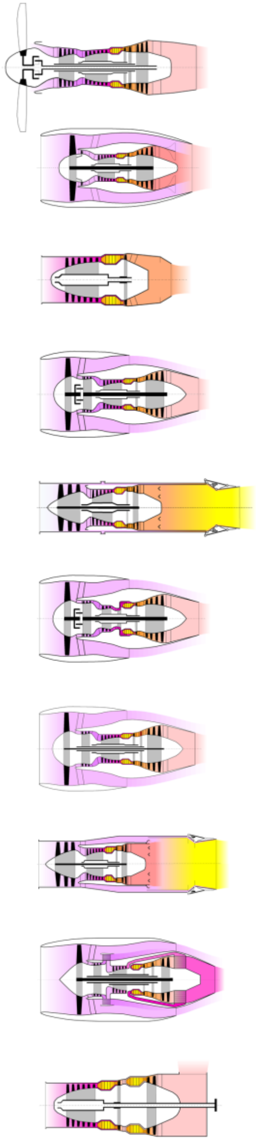
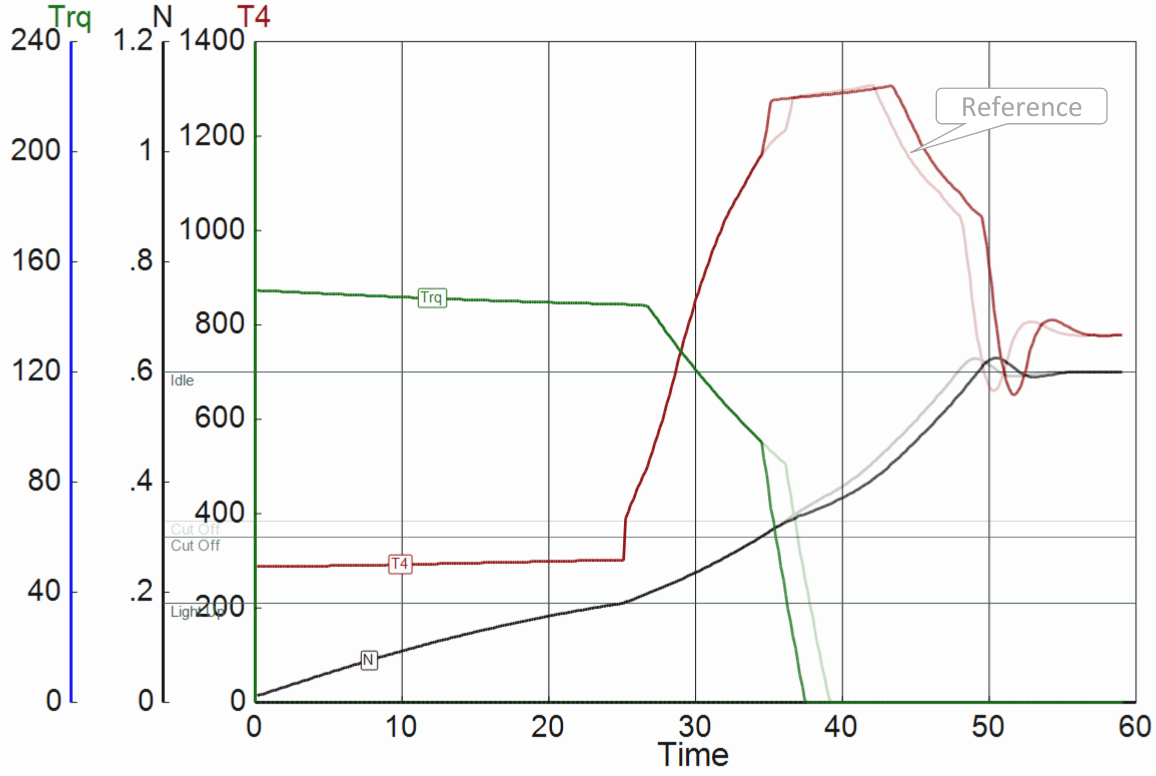
Starter Cut-off Speed
From 0.3 to 0.33





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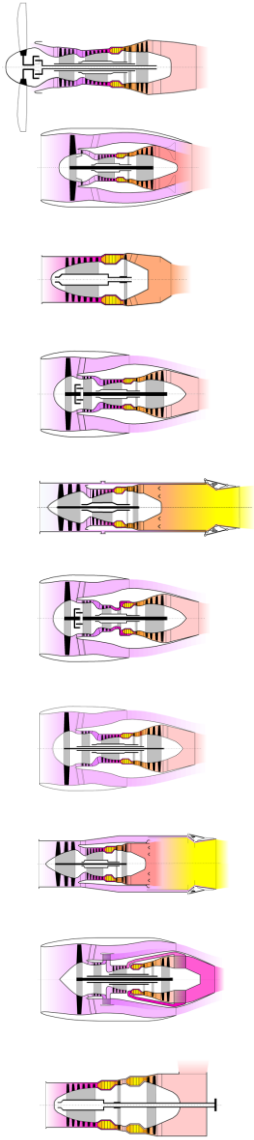

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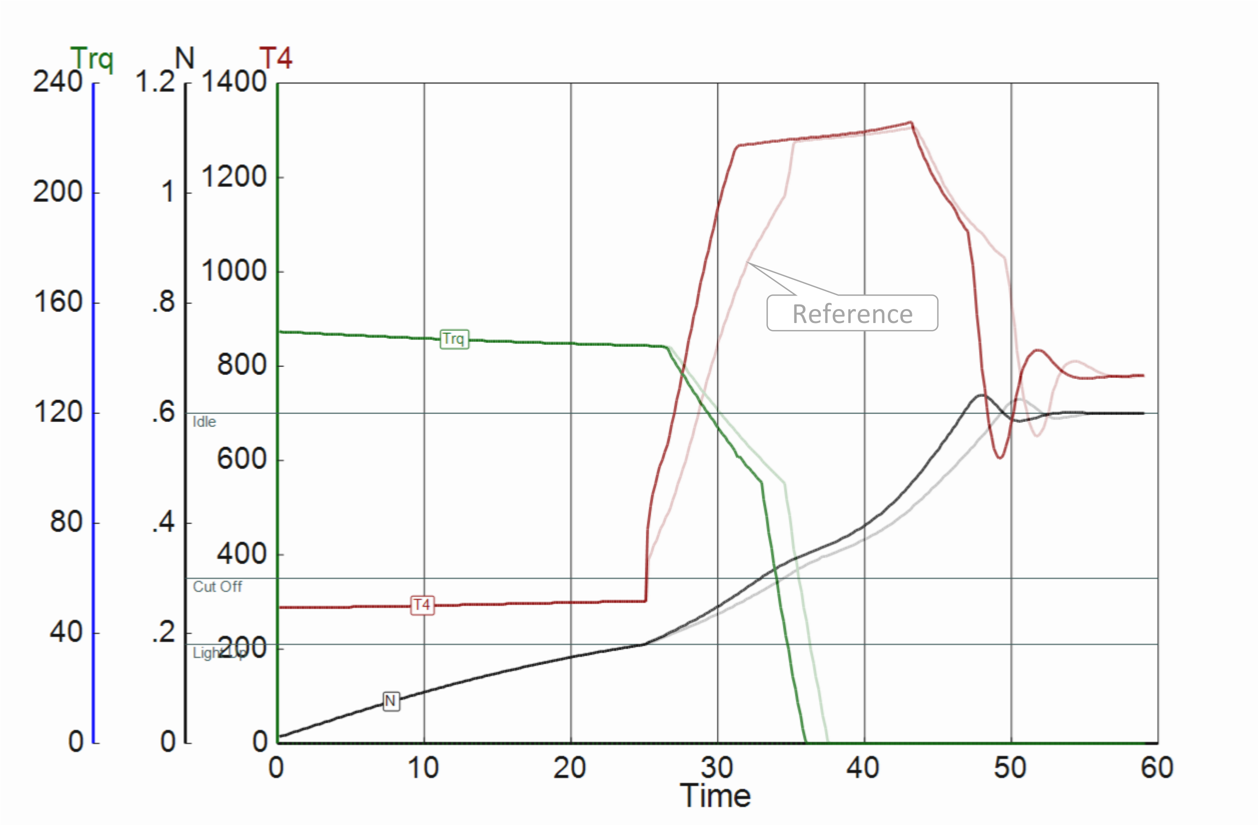
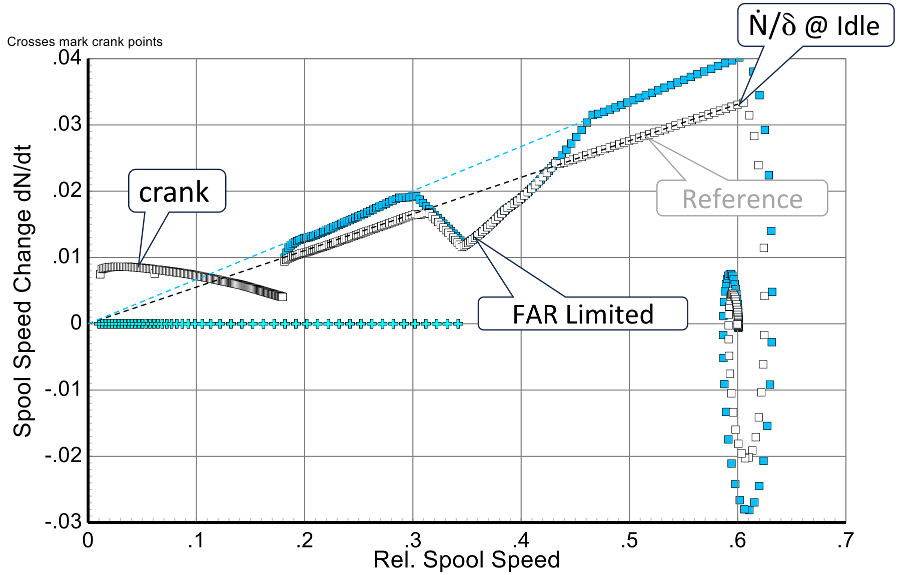
Acceleration Rate Limiter $\dot{N}/\delta$ @ Idle

From 0.033 to 0.04





Note:
The scheduled $\dot{N}/\delta$ increases linearly from light-up to idle speed. This approach prevents an overly large step in T_4 at light-up.

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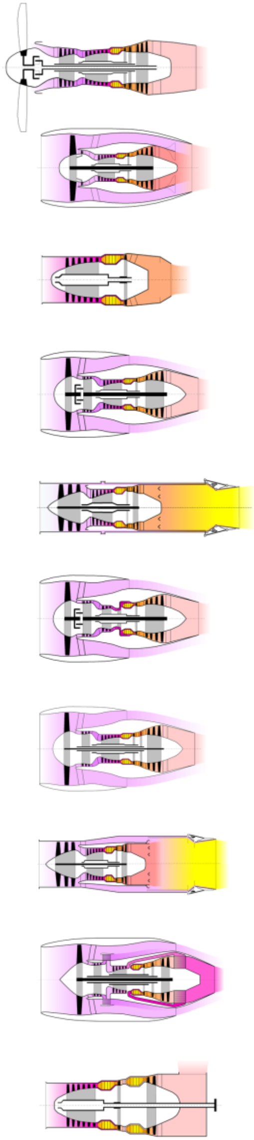
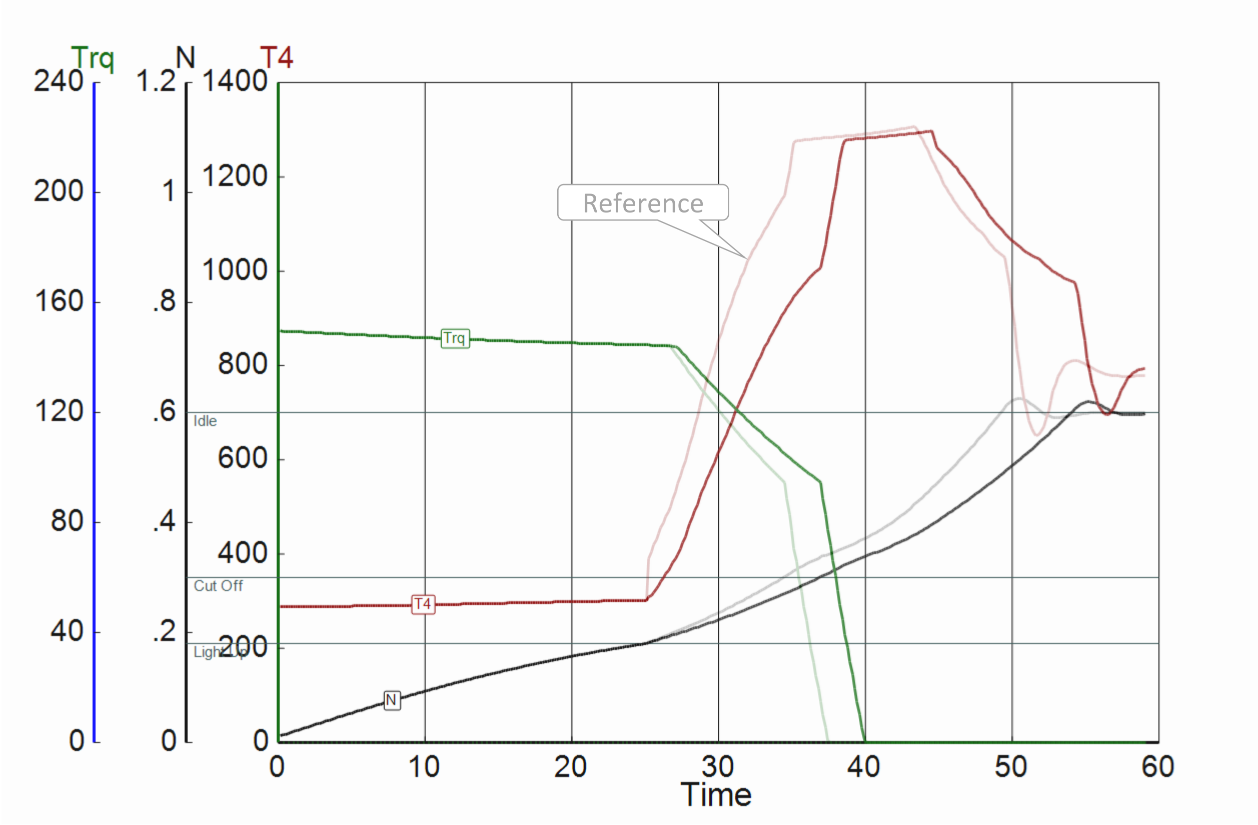
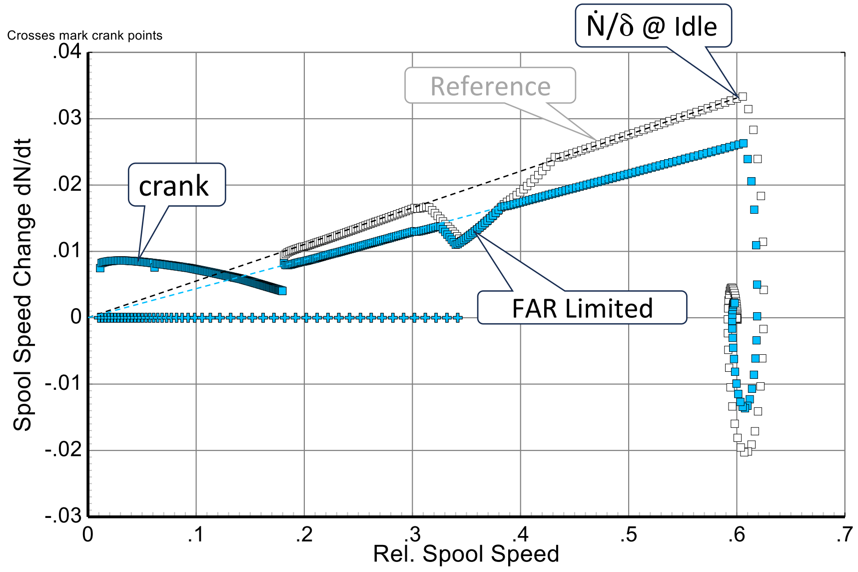
Acceleration Rate Limiter $\dot{N}/\delta$ @ Idle

From 0.033 to 0.026







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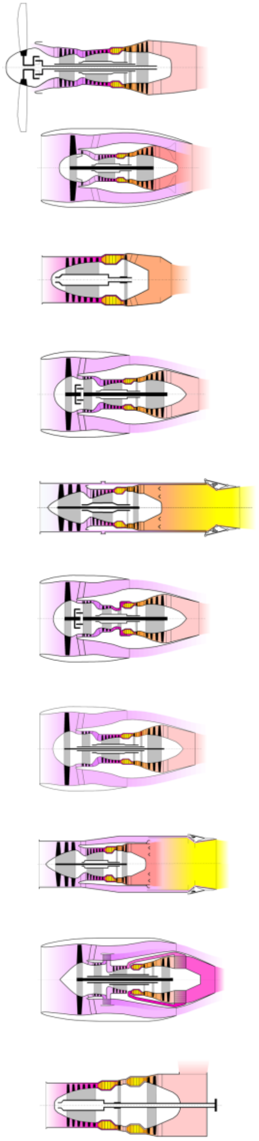
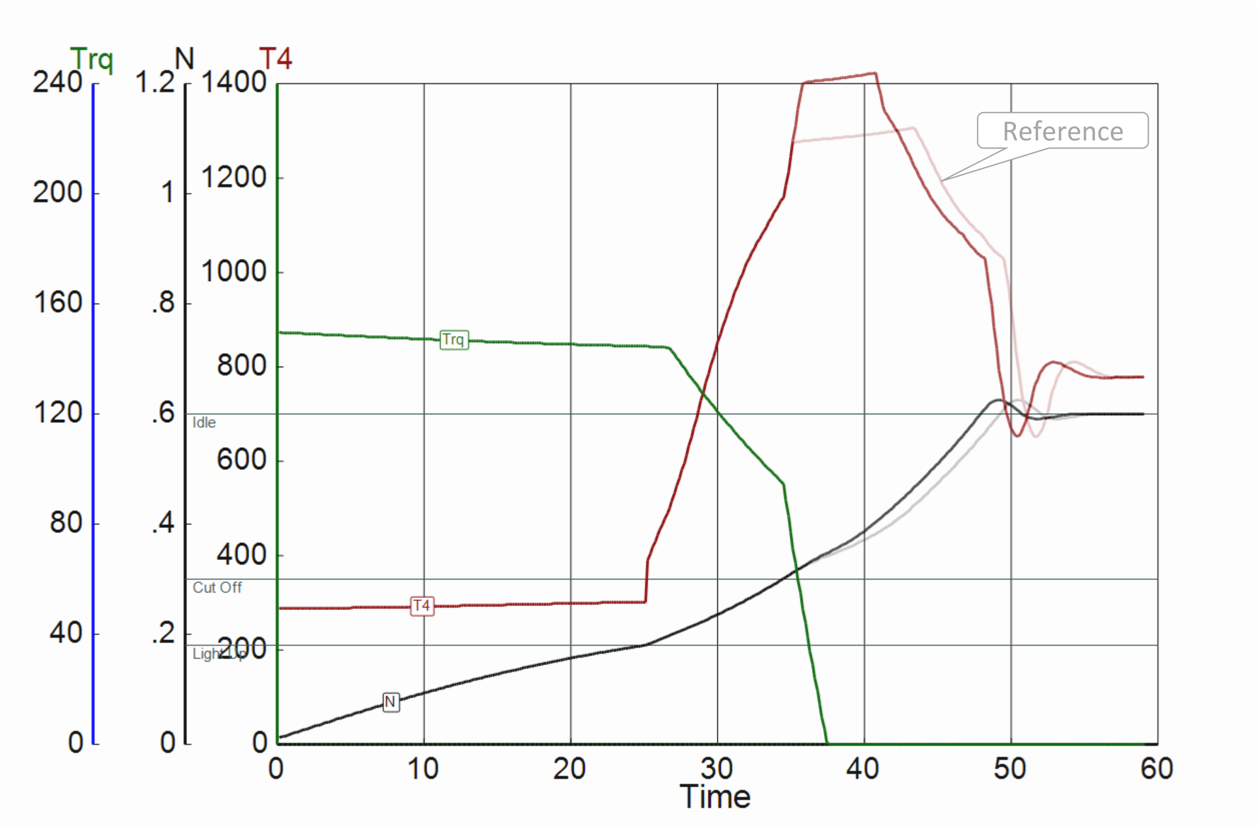
FAR_{max} Limiter
From 0.026 to 0.03





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T_5 Limiter
Introduced as 1050K

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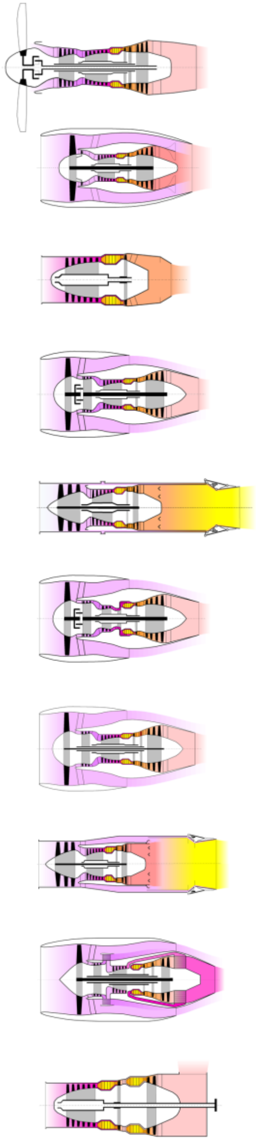

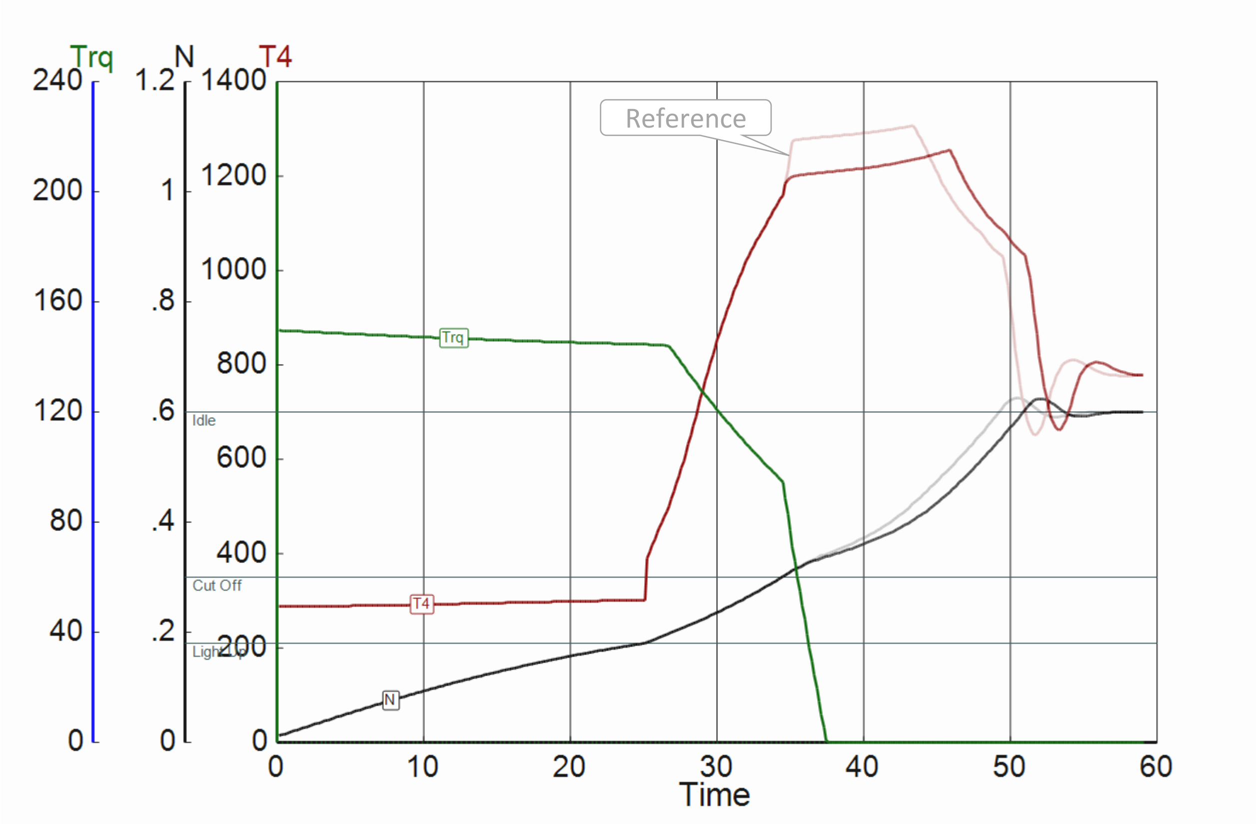

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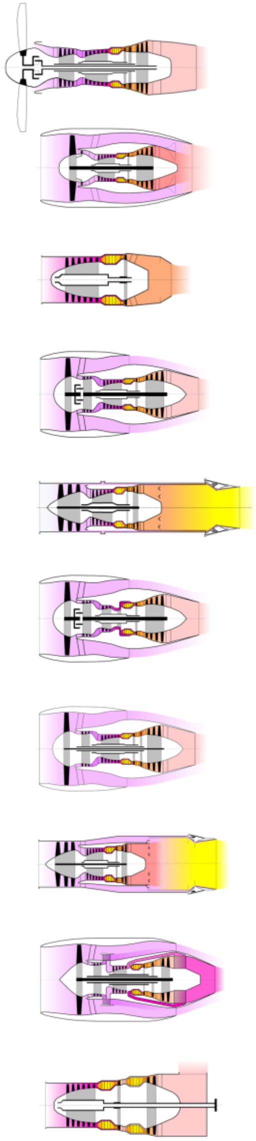
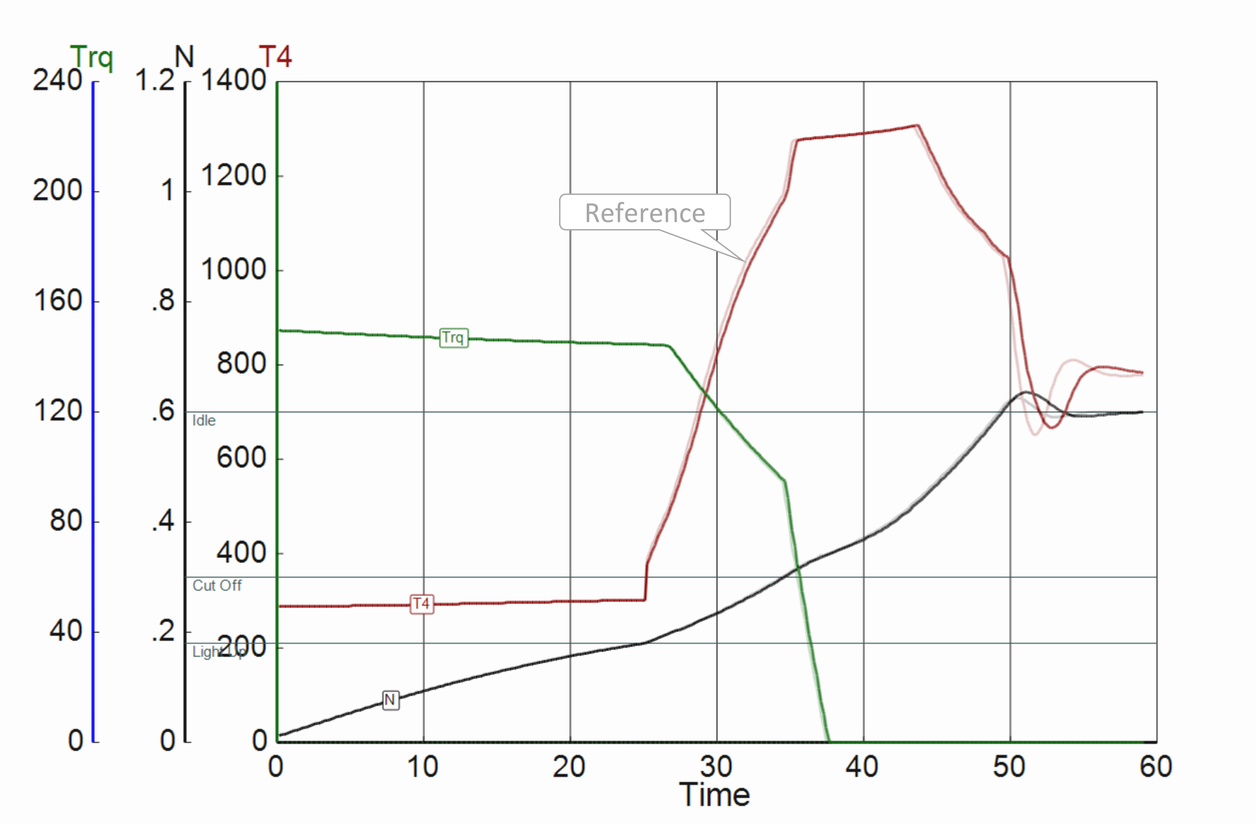


Proportional Control Constant

From 0.04 to 0.02 (-50%)



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Integral Control Constant

From 0 to 1

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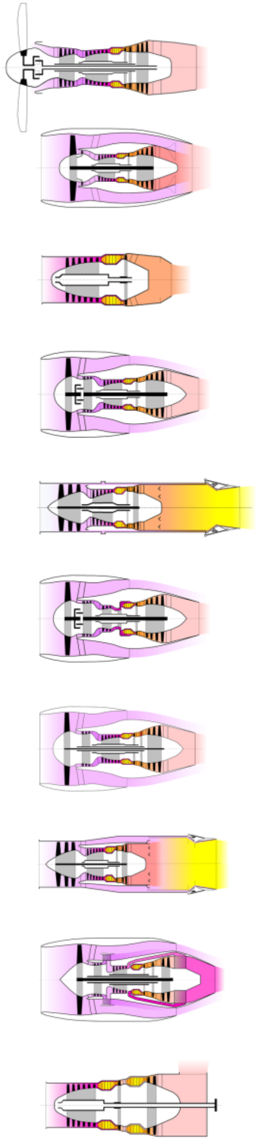

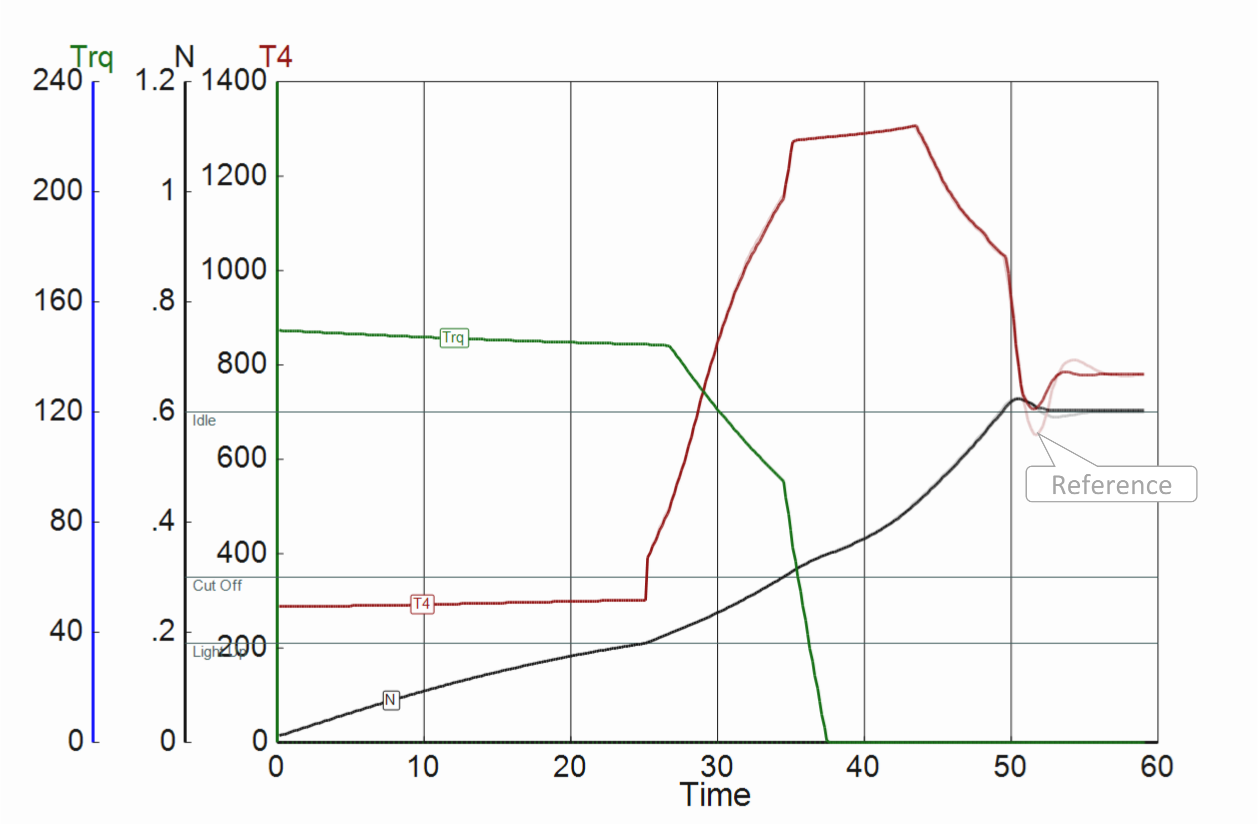

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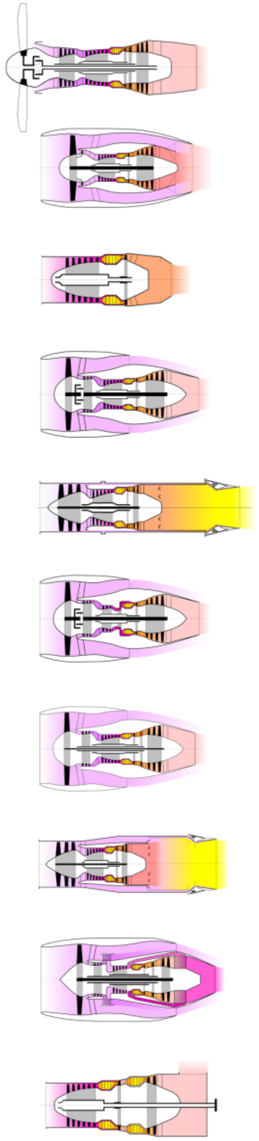
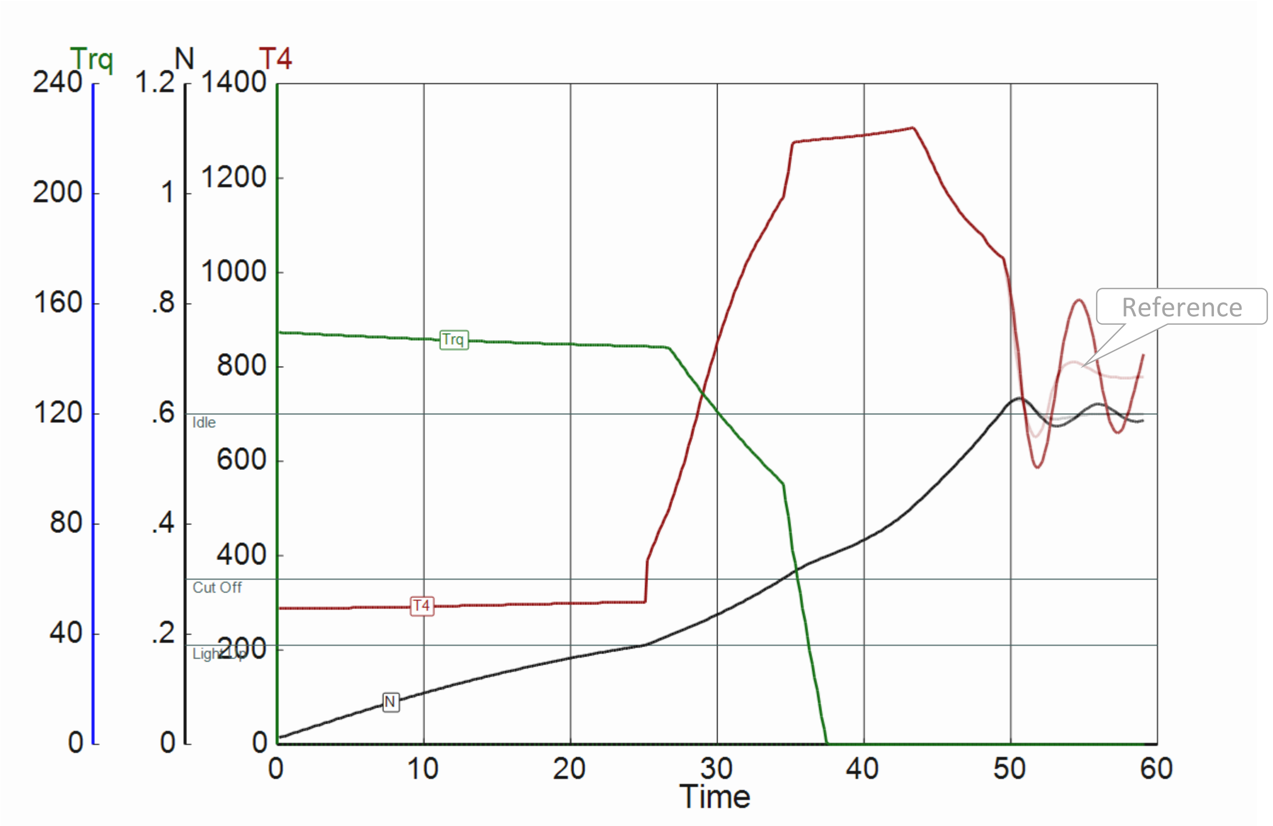


Differential Control Constant
From 0.04 to 0



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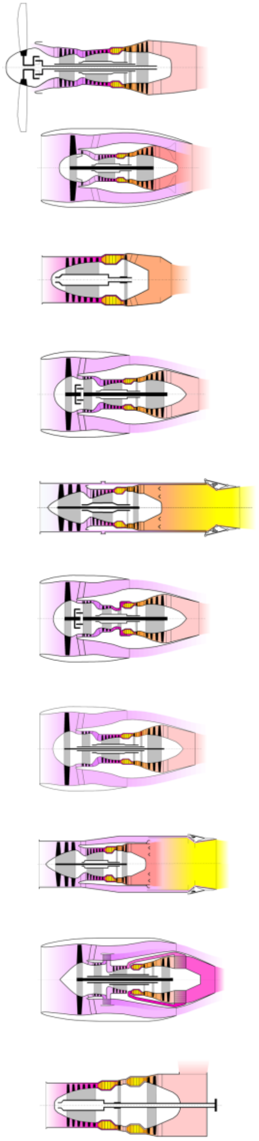
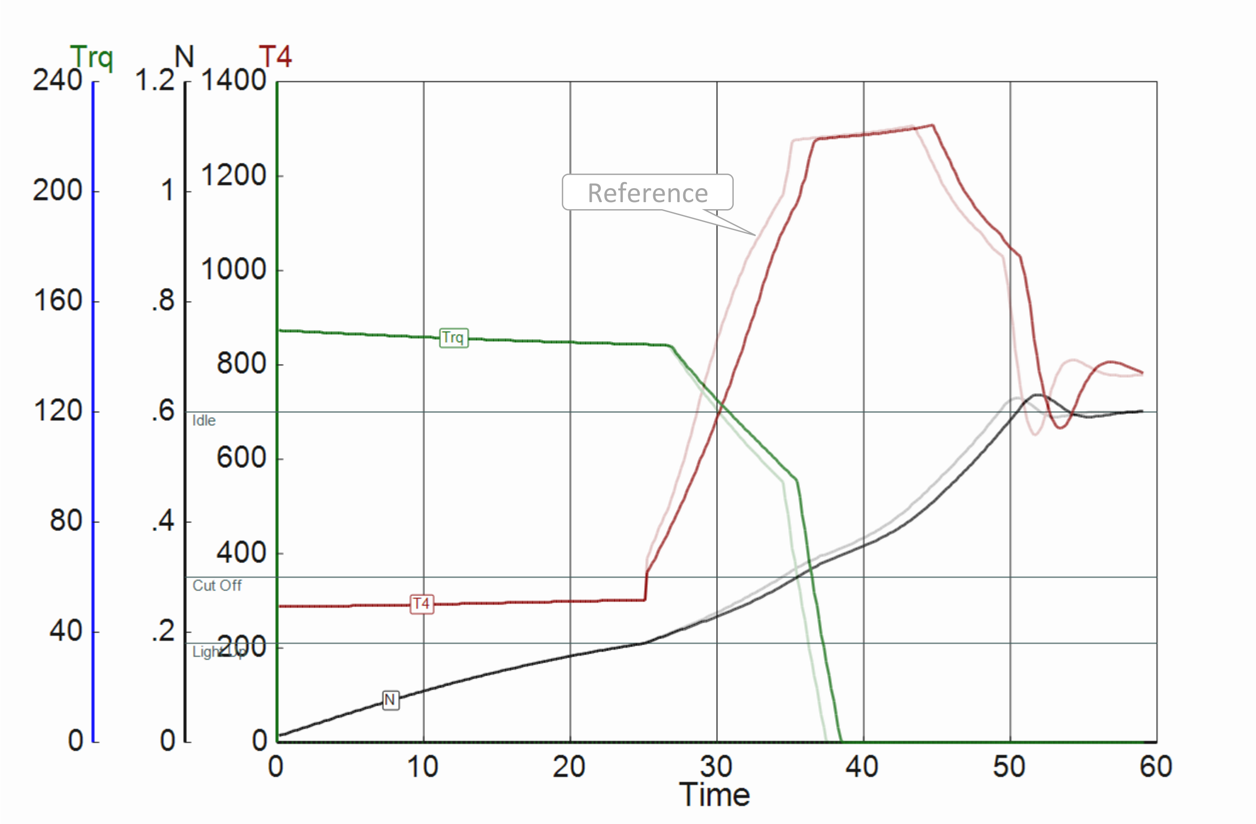
Gain Modifier
From 1 to 2





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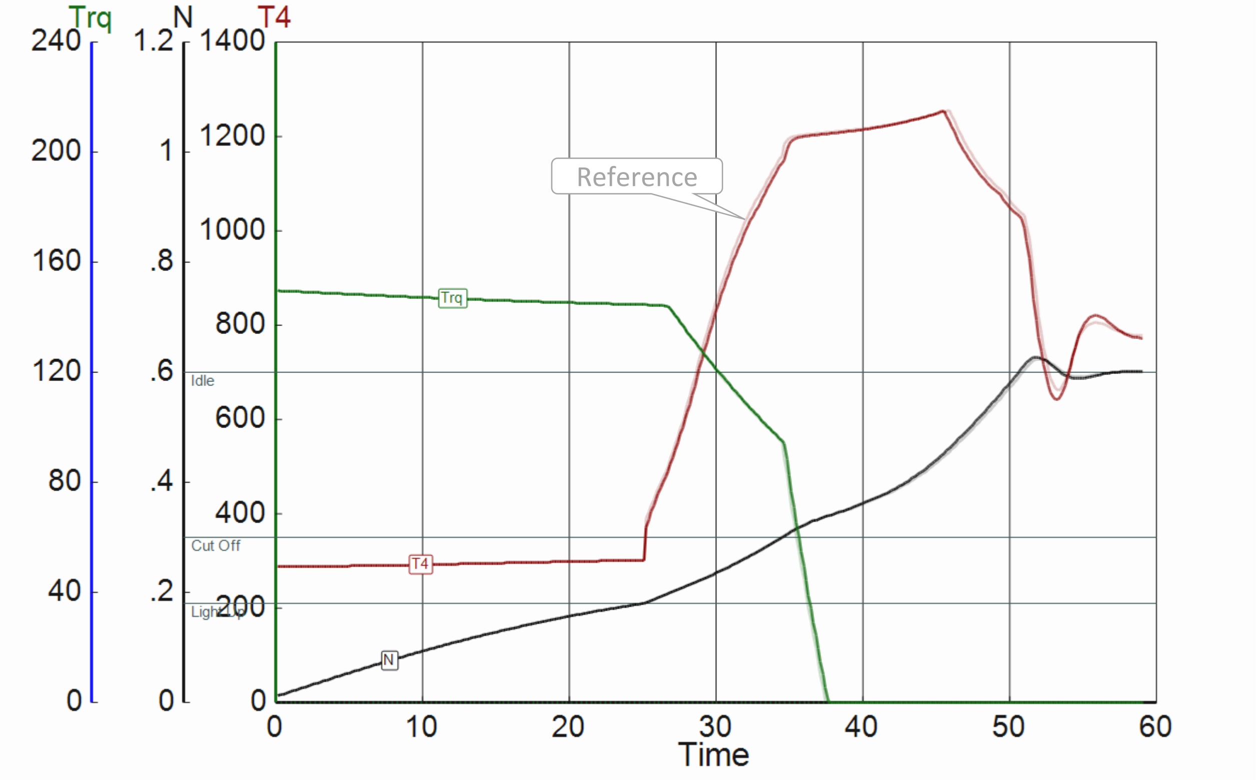
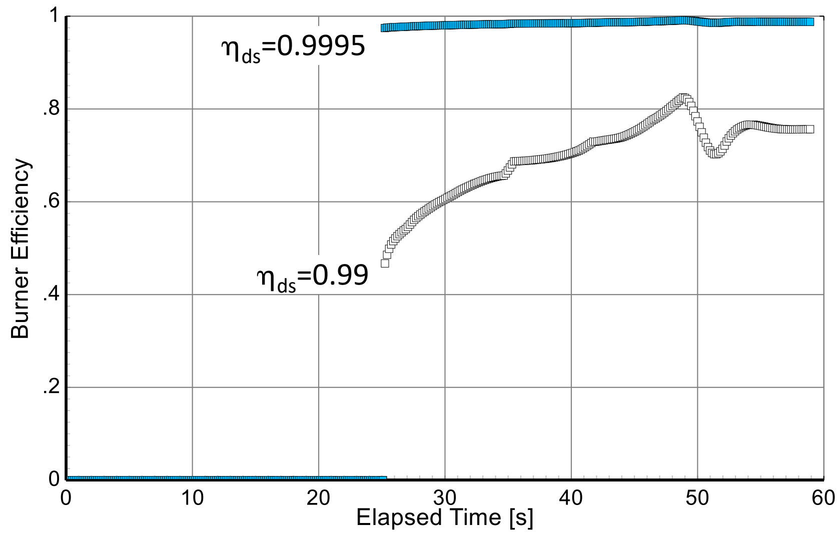
Effect of Burner Efficiency
$T_{5,max}$ =1050K



Burner efficiency is calculated as

$$\log(1-\eta) = \log(1-\eta_{ds}) + 1.6 \times \log(\Omega/\Omega_{ds})$$



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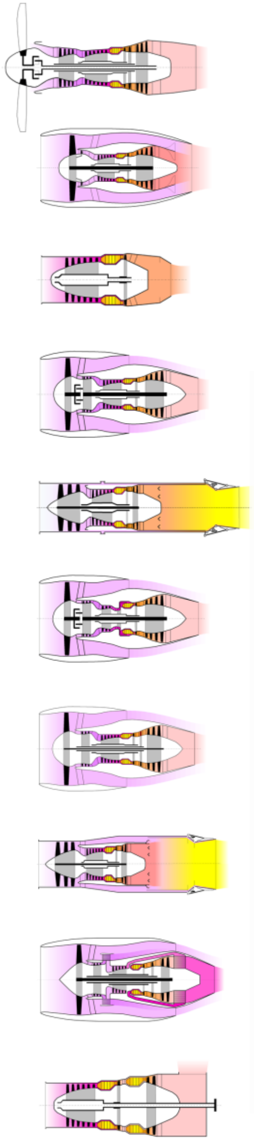
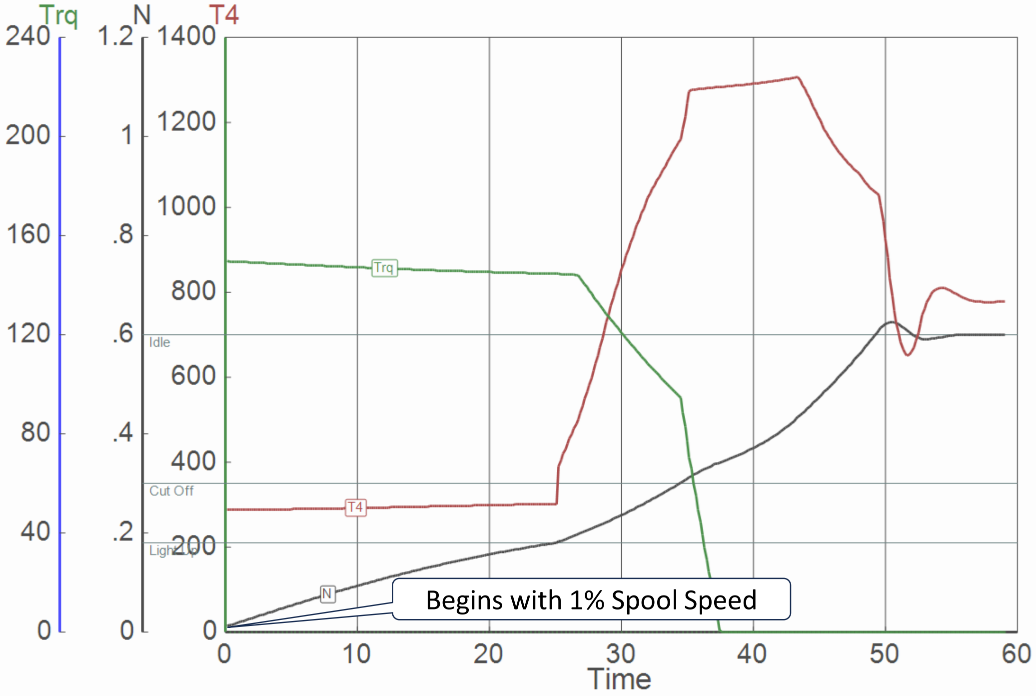
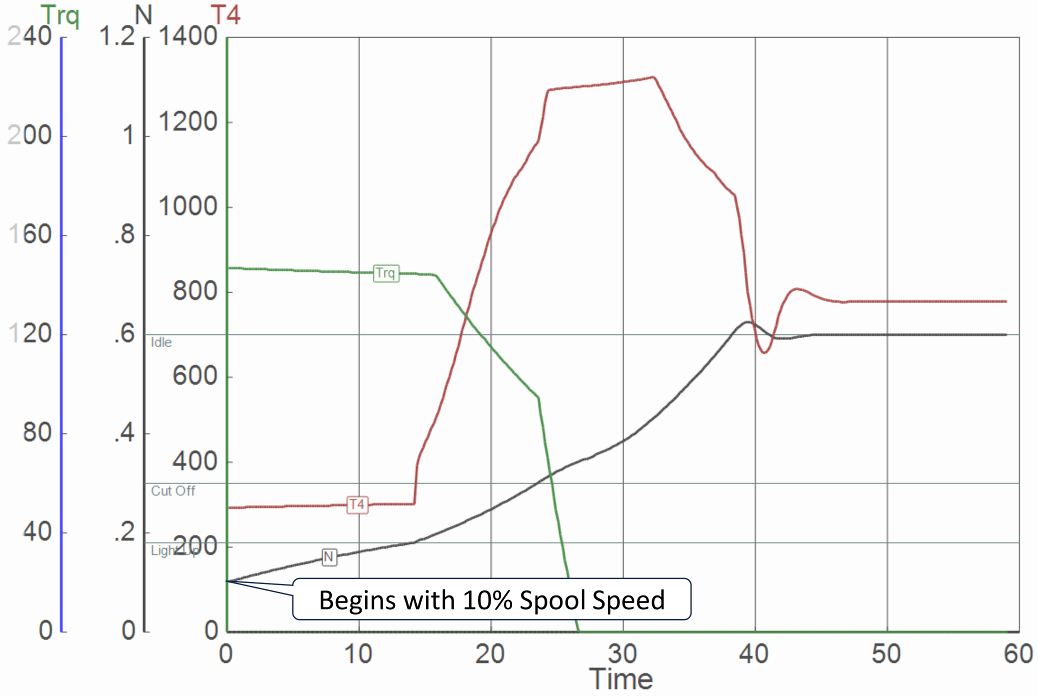


Compressor Map Extension

Reference Map
Split ß-Line Grid*
N/√Θ = 1% ...105%



Conventional Map
Standard ß-Line Grid
N /√Θ = 10% ...105%



* see chapter 18 in "Propulsion and Power", 2nd Edition

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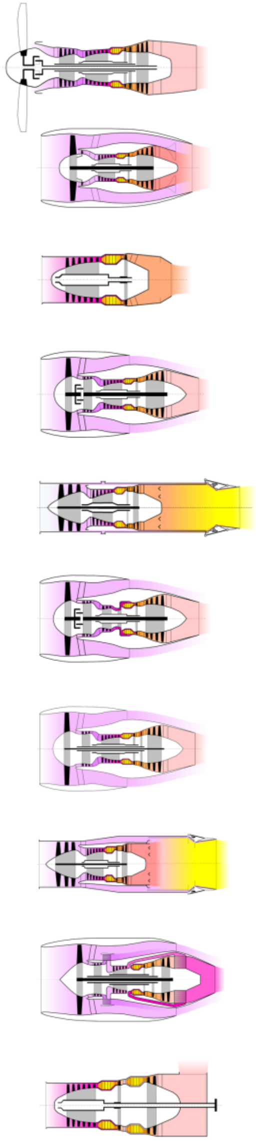
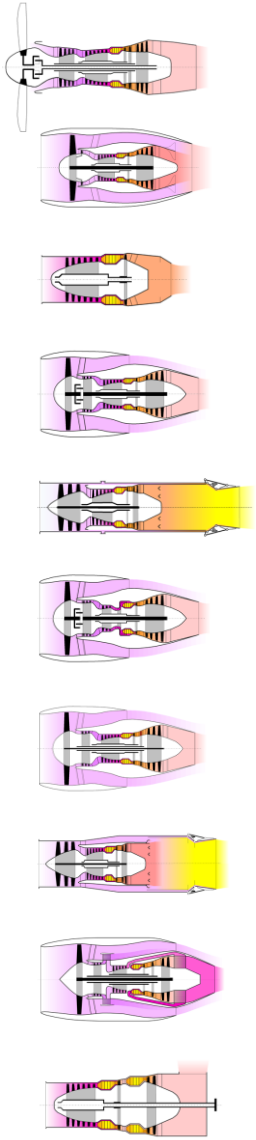


Windmilling

Preparing a Windmilling Simulation



Create an engine model consisting of

- The thermodynamic cycle reference point
- Extended compressor and turbine maps
  - Downto very low speed (10% … 5%)
  - Include compressor pressure ratio region with P/P<1

Find a suitable starting point for the simulation

- A zero fuel flow point at a low spool speed and Mach number > 0 is required
  - Run a zero Mach number steady state case with 30% spool speed
  - Increase Mach number in small steps – fuel flow will decrease.
  - Select a point with low fuel flow
  - Switch to windmilling mode

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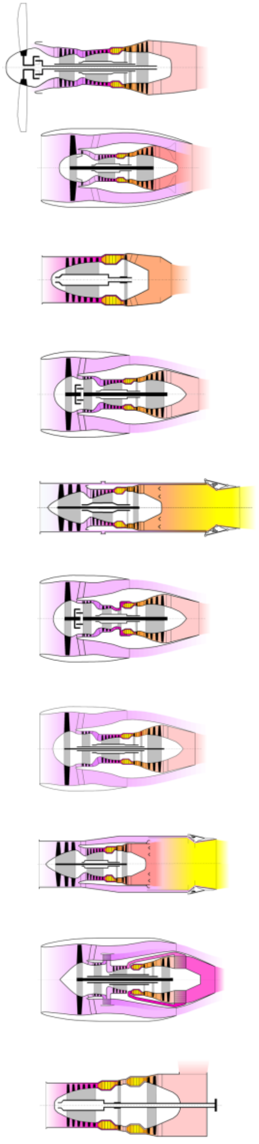

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Steady State Operation

30% Spool Speed

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		288.15	101.325	
1	2.313	288.15	101.325	
2	2.313	288.15	101.325	2.313
3	2.313	337.54	136.838	1.853
31	1.987	337.54	136.838	
4	2.027	1087.70	135.028	2.955
41	2.189	1037.21	135.028	3.116
49	2.189	992.25	102.390	
5	2.327	956.36	102.390	4.196
6	2.327	956.36	102.390	
8	2.327	956.36	102.390	4.196
Bleed	0.025	337.54	136.838	

P2/P1 = 1.0000 P4/P3 = 0.9868 P6/P5 1.0000

Efficiencies:	isentr	polytr	RNI	P/P
Compressor	0.5217	0.5415	1.000	1.350
Burner	0.9826			0.987
Turbine	0.6663	0.6588	0.296	1.319

Spool mech Eff 0.9900 Speed 30.00 %

hum [%]	war0	FHV	Fuel
0.0	0.00000	42.769	Generic

SL static, ISA , Rel GG Speed=0.300

FN	=	0.18 kN	Net Thrust
TSFC	=	227.3385 g/(kN*s)	Thrust Specific Fuel Consumption
FN/W2	=	76.22 m/s	Specific Thrust
Prop Eff	=	0.0000	Propulsion Efficiency
eta core	=	0.0039	Core Efficiency
P5/P2	=	1.0105 EPR	Engine Pressure Ratio
WF	=	0.04007 kg/s	Fuel Flow
s NOx	=	0.02662	NOx Severity Parameter
XM8	=	0.1256	Nozzle Throat Mach No.
A8	=	0.0881 m²	Geometric Nozzle Throat Area
P8/Pamb	=	1.0105	Nozzle Pressure Ratio
WBld/W2	=	0.01100	Bleed Air Flow/Mass Flow W2
Ang8	=	16.00 deg	Nozzle Petal Angle
CD8	=	0.9427	Nozzle Discharge Coefficient
WClN/W2	=	0.07000	Turbine Nozzle Guide Vane Cooling Air / W2
WClR/W2	=	0.06000	Turbine Rotor Cooling Air/ W2
Loading	=	919.88 %	Burner Loading in % of the Cycle Design Point Value
e45 th	=	0.65477	Thermodynamic Turbine Efficiency
far8	=	0.01752	Nozzle Throat Fuel-Air-Ratio
PWX	=	0.00 kW	Power Offtake

Standard off-design iteration setup for a given speed	
Variable	Error
Beta in HPC Map	*Turbine Flow*
T4	*Turbine Pressure Ratio*
Beta in HPT Map	*Nozzle Pressure Ratio*

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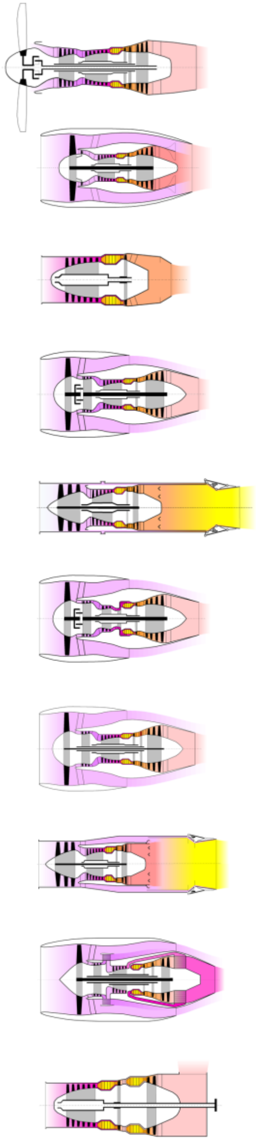
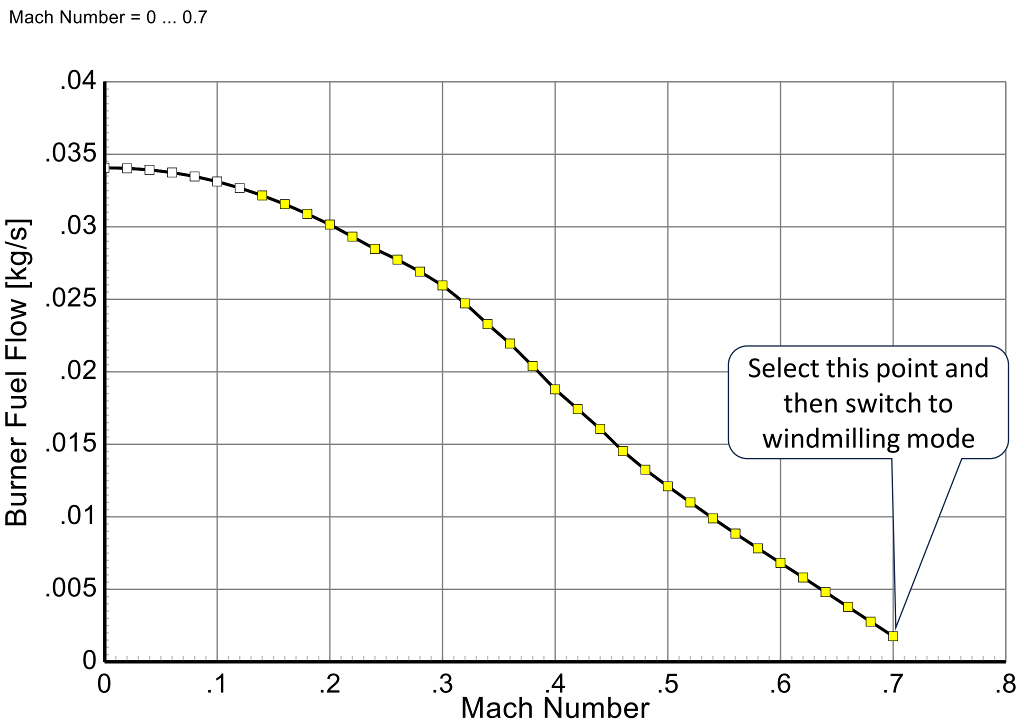


Parametric Study With Increasing Flight Mach Number



One might encounter convergence problems when switching from a normal, steady-state performance point with a given spool speed to a windmilling point. In such a case, run a parametric study with an increasing Mach number. Select a point with low fuel flow from this study, treat it as a normal off-design point, and then switch to windmilling.

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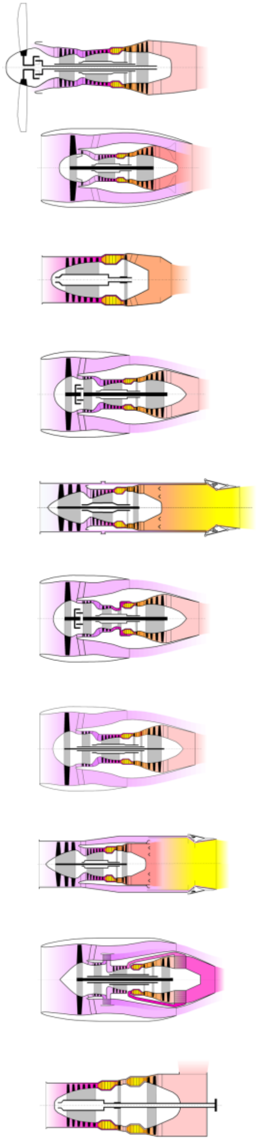

Steady State Operation
Windmilling at 30% Spool Speed

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```
            W          T          P          WRstd
Station  kg/s          K        kPa          kg/s
 amb               288.15    101.325
  1       5.859    318.17    143.401
  2       5.859    318.17    143.401         4.350
  3       5.859    345.06    171.777         3.782
 31       5.033    345.06    171.777
  4       5.033    345.06    162.318         3.438
 41       5.443    345.06    162.318         3.718
 49       5.443    315.82    103.652
  5       5.795    317.59    103.652         5.947
  6       5.795    317.59    103.652
  8       5.795    317.59    103.652         5.947
Bleed     0.064    345.06    171.779
---------------------------------------------
P2/P1 = 1.0000  P4/P3 = 0.9449  P6/P5 1.0000
Efficiencies:   isentr  polytr    RNI    P/P
 Compressor     0.6242  0.6336  1.258  1.198
 Burner         0.0000                 0.945
 Turbine        0.7067  0.6933  1.293  1.566
---------------------------------------------
Spool mech Eff  0.9900  Speed        30.00 %
---------------------------------------------
 hum [%]     war0        FHV      Fuel
    0.0   0.00000     42.769     Generic
```

```
SL Mn=0.722 ISA ,  Rel GG Speed=0.300,  windmilling

FN        =     -1.07 kN           Net Thrust
TSFC      =    0.0000 g/(kN*s)     Thrust Specific Fuel Consumption
FN/W2     =   -182.24 m/s          Specific Thrust

Prop Eff  =    1.5855              Propulsion Efficiency
eta core  =    0.0000              Core Efficiency
P5/P2     =    0.7228 EPR          Engine Pressure Ratio
WF        =   0.00000 kg/s         Fuel Flow
s NOx     =   0.00000              NOx Severity Parameter
XM8       =    0.1805              Nozzle Throat Mach No.
A8        =    0.0881 m²           Geometric Nozzle Throat Area
P8/Pamb   =    1.0230              Nozzle Pressure Ratio
WBld/W2   =   0.01100              Bleed Air Flow/Mass Flow W2
Ang8      =     16.00 deg          Nozzle Petal Angle
CD8       =    0.9154              Nozzle Discharge Coefficient
WClN/W2   =   0.07000              Turbine Nozzle Guide Vane Cooling Air / W2
WClR/W2   =   0.06000              Turbine Rotor Cooling Air/ W2
Loading   =   1509.42 %            Burner Loading in % of the Cycle Design Point Value
e45 th    =   0.00000              Thermodynamic Turbine Efficiency
far8      =   0.00000              Nozzle Throat Fuel-Air-Ratio
PWX       =      0.00 kW           Power Offtake
```

Windmilling iteration setup, spool speed is given	
Variable	Error
Beta in HPC Map	*Turbine Flow*
Mach number XM	*Turbine Pressure Ratio*
Beta in HPT Map	*Nozzle Pressure Ratio*

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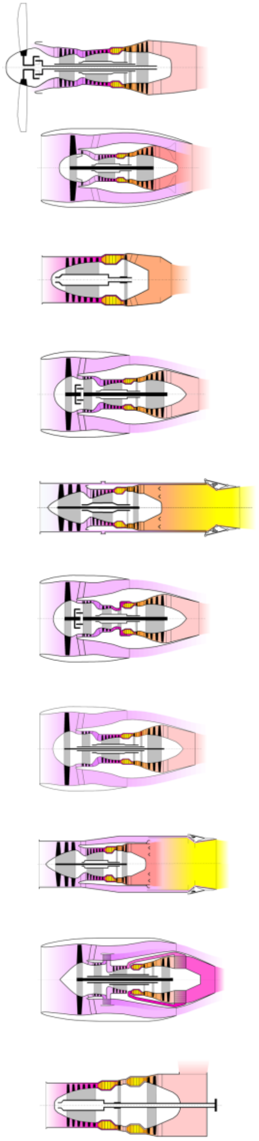
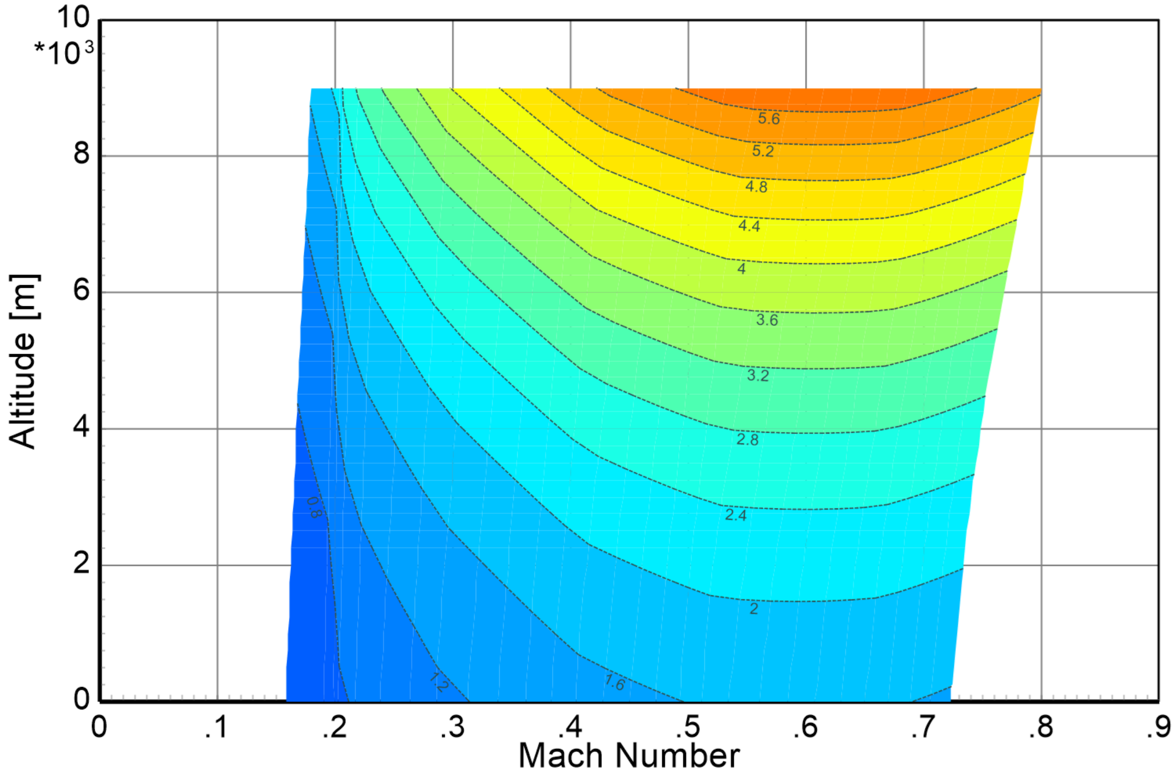


Windmilling

Burner Loading Relative to Idle Sea Level Static



Burner loading during windmilling is an indicator of the difficulty encountered during a relight, which can be a significant challenge.

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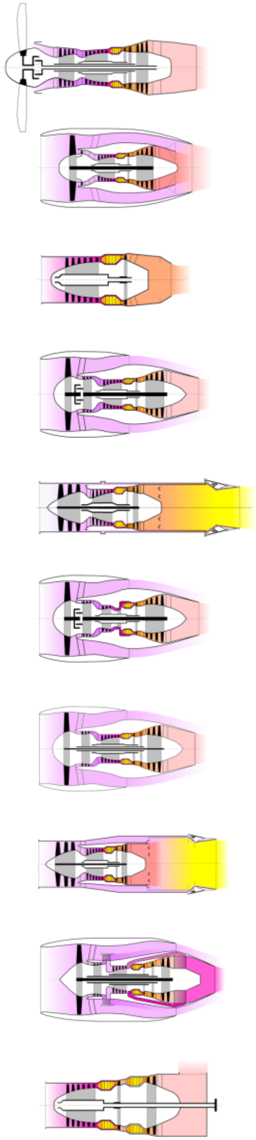

Windmilling
Shaft Power Available = f(N,Mach)

Altitude 1000m, ISA

Altitude 5000m, ISA

Note:
Power Available is calculated as $(1-\eta_{mech})*PW_{Turbine}$

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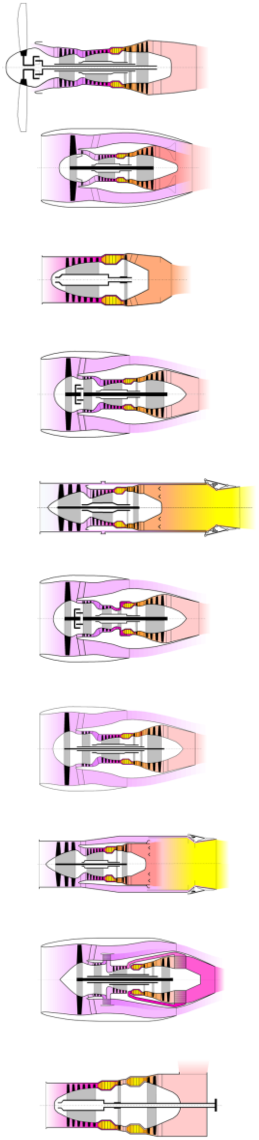

Windmilling in the Component Maps

$PW_X = (1-\eta_{mech}) * PW_{Turbine}$

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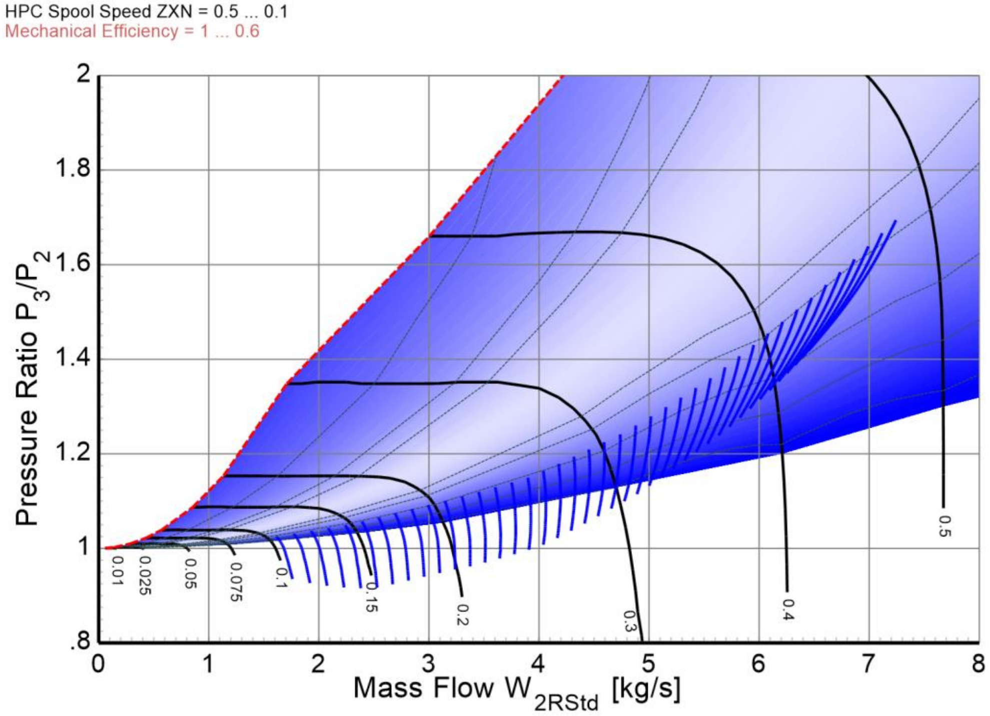

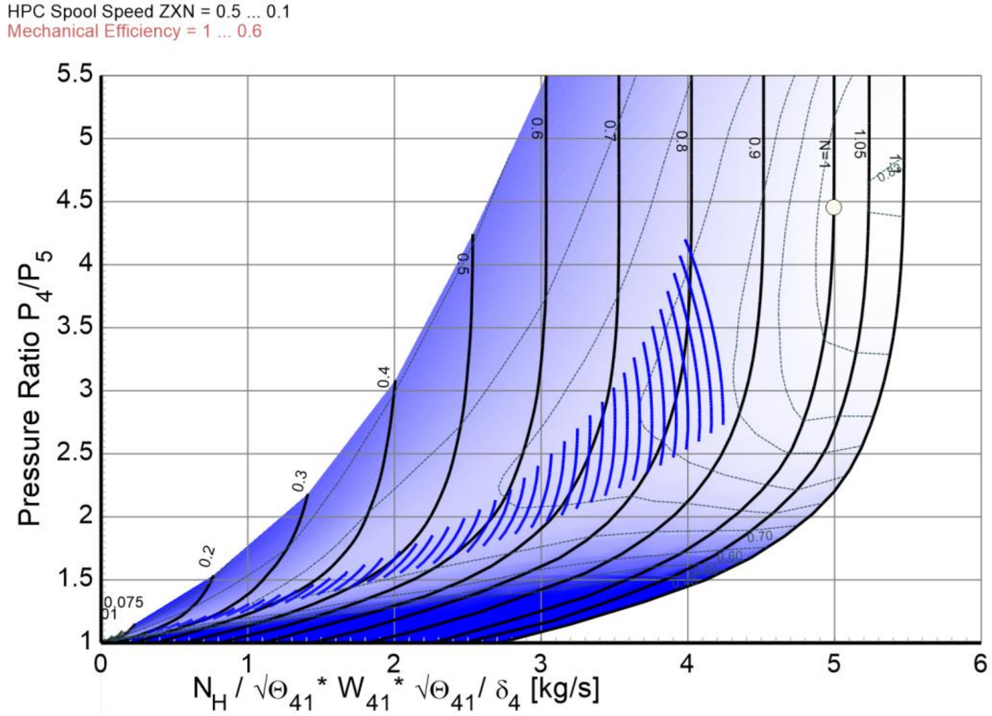

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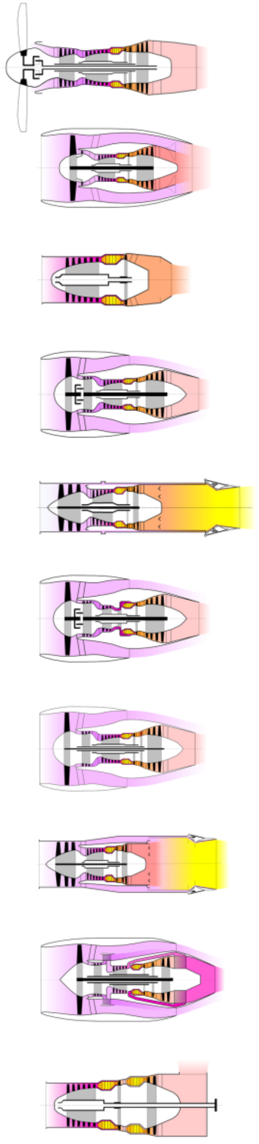

A Windmilling Relight Example

Altitude 6000m, Mach=0.44

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```
         W         T          P          WRstd
Station  kg/s      K          kPa        kg/s
 amb               249.15     47.181
  1      1.354     258.80     53.881
  2      1.354     258.80     53.881     2.413
  3      1.354     266.07     56.903     2.317
 31      1.163     266.07     56.903
  4      1.163     266.07     55.727     2.032
 41      1.258     266.07     55.727     2.198
 49      1.258     258.16     47.377
  5      1.339     258.64     47.377     2.714
  6      1.339     258.64     47.377
  8      1.339     258.64     47.377     2.714
Bleed    0.015     266.07     56.903
--------------------------------------------
P2/P1 = 1.0000   P4/P3 = 0.9793  P6/P5 1.0000
Efficiencies:    isentr  polytr    RNI    P/P
 Compressor      0.5596  0.5630  0.604  1.056
 Burner          0.0000                 0.979
 Turbine         0.6552  0.6499  0.604  1.176
--------------------------------------------
Spool mech Eff   0.9900  Speed        15.00 %
--------------------------------------------
 hum [%]     war0       FHV      Fuel
    0.0   0.00000    42.769    Generic
```

```
Alt= 6000m / Mn=0.440 ISA ,  Rel GG Speed=0.150,  windmilling

FN        =    -0.16 kN           Net Thrust
TSFC      =   0.0000 g/(kN*s)     Thrust Specific Fuel Consumption
FN/W2     =  -114.61 m/s          Specific Thrust

Prop Eff  =   1.6975              Propulsion Efficiency
eta core  =   0.0000              Core Efficiency
P5/P2     =   0.8793 EPR          Engine Pressure Ratio
WF        =  0.00000 kg/s         Fuel Flow
s NOx     =  0.00000              NOx Severity Parameter
XM8       =   0.0769              Nozzle Throat Mach No.
A8        =   0.0881 m²           Geometric Nozzle Throat Area
P8/Pamb   =   1.0042              Nozzle Pressure Ratio
WBld/W2   =  0.01100              Bleed Air Flow/Mass Flow W2
Ang8      =    16.00 deg          Nozzle Petal Angle
CD8       =   0.9639              Nozzle Discharge Coefficient
WClN/W2   =  0.07000              Turbine Nozzle Guide Vane Cooling Air / W2
WClR/W2   =  0.06000              Turbine Rotor Cooling Air/ W2
Loading   =  1684.95 %            Burner Loading in % of the Cycle Design Point Value
e45 th    =  0.00000              Thermodynamic Turbine Efficiency
far8      =  0.00000              Nozzle Throat Fuel-Air-Ratio
PWX       =     0.00 kW           Power Offtake
```

Windmilling iteration setup, spool speed is given	
Variable	Error
Beta in HPC Map	*Turbine Flow*
Mach number XM	*Turbine Pressure Ratio*
Beta in HPT Map	*Nozzle Pressure Ratio*

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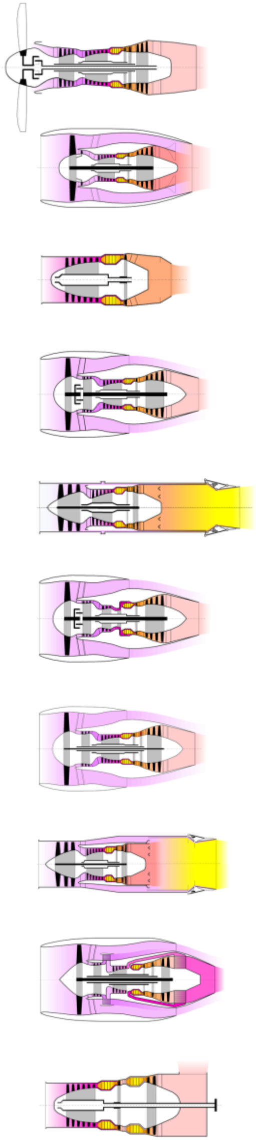

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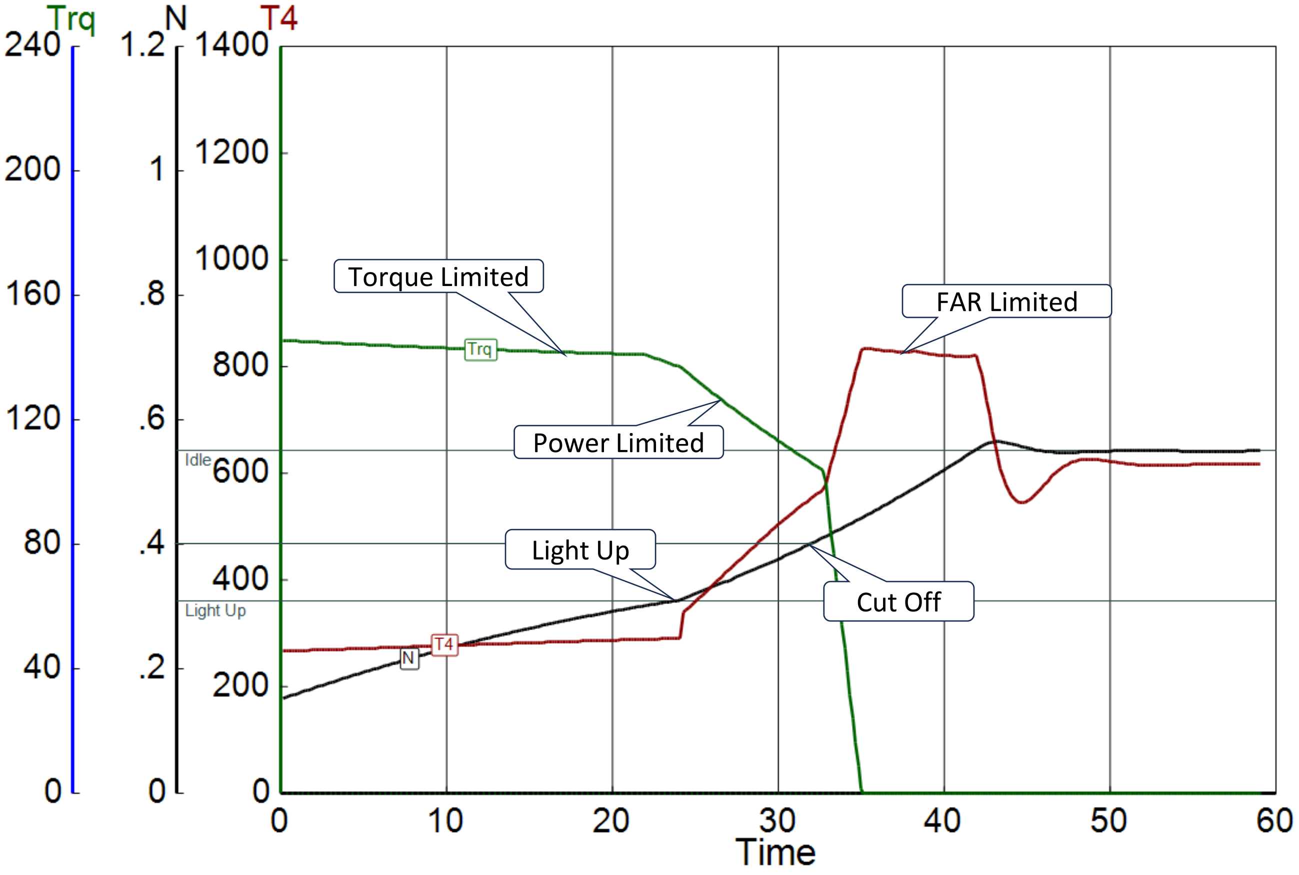
Windmill Relight



Adjust the numbers for light-up, starter cut-off speed and max starter power:

Rotor Inertia	kg m^2	5.69
Rel N for PLA 0% (Idle)		0.6
Proportional Control Constant		0.04
Integral Control Constant		0
Differential Control Constant		0.04
Gain Modifier		1
Minimum Fuel-Air-Ratio		0.003
Maximum Fuel-Air-Ratio		0.026
Decel (dN/dt)/(P2/Pstd) Limit		0.1
Accel (dN/dt)/(P2/Pstd) Limit		0.033
Rel. Burner Light-up Speed		**0.31**
Rel. Starter Cut-off Speed		**0.4**
Max Starter Torque	N m	150
Starter Torque Slope		-0.2
Max Starter Power	kW	**60**

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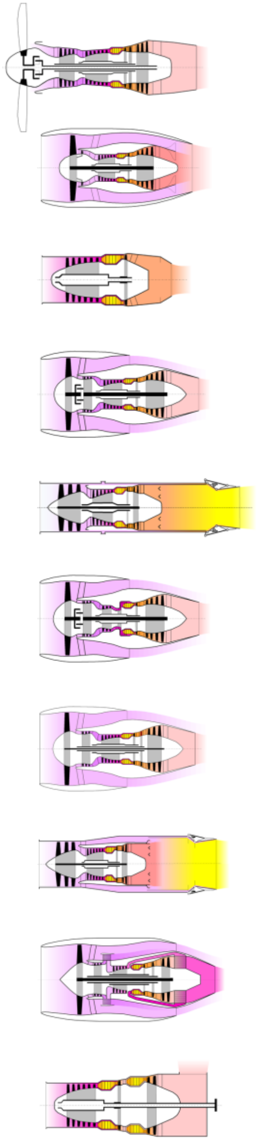

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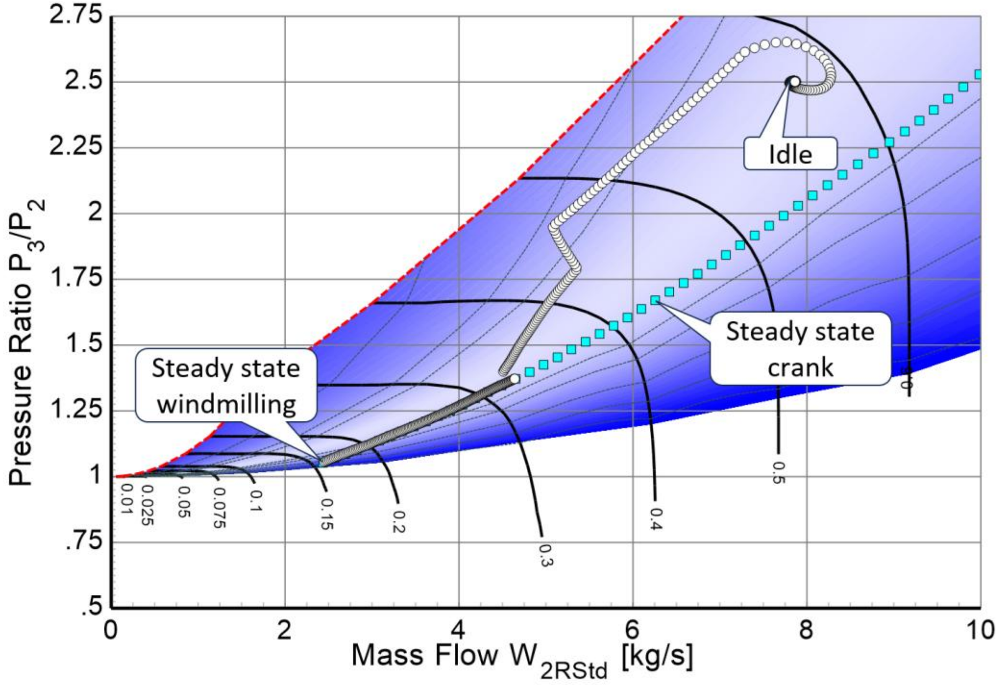
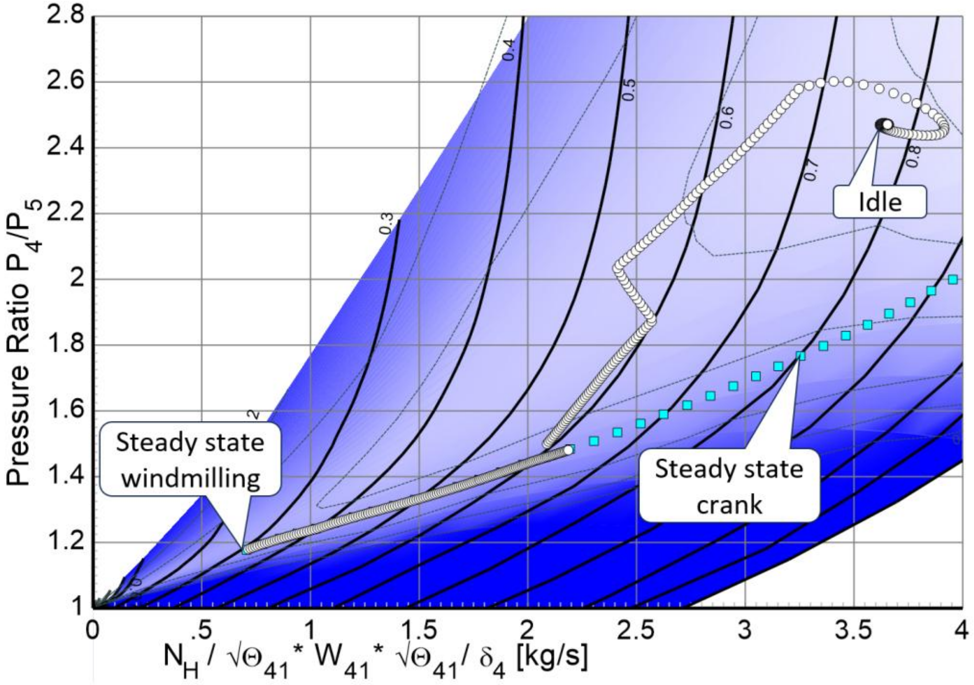
Windmill Relight





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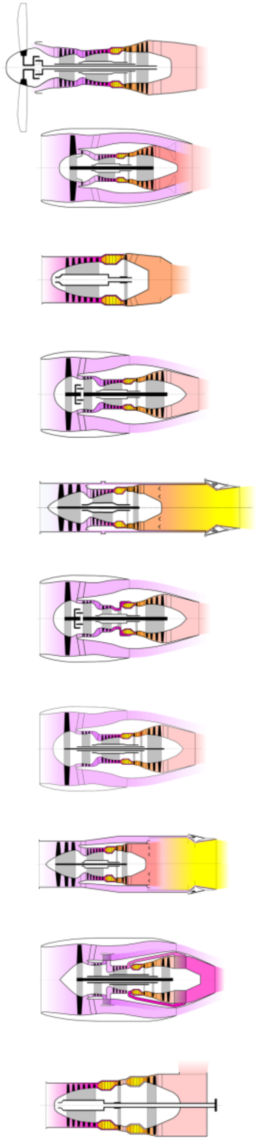

Concluding Remarks

This tutorial focused on the most basic type of gas turbine:
a single-spool machine.

- The starting process for more complex engines with multiple spools is similar when the starter motor is connected to the gas generator spool. The compressors and turbines on the other spools are accelerated by the gas generator's exhaust.
- Windmilling of high bypass ratio turbofans is dominated by the behavior of the fan.
- However, the procedures for simulating starting and windmilling remain the same.

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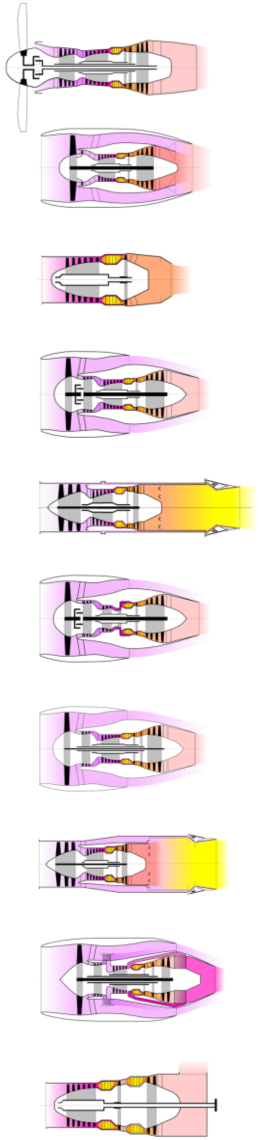
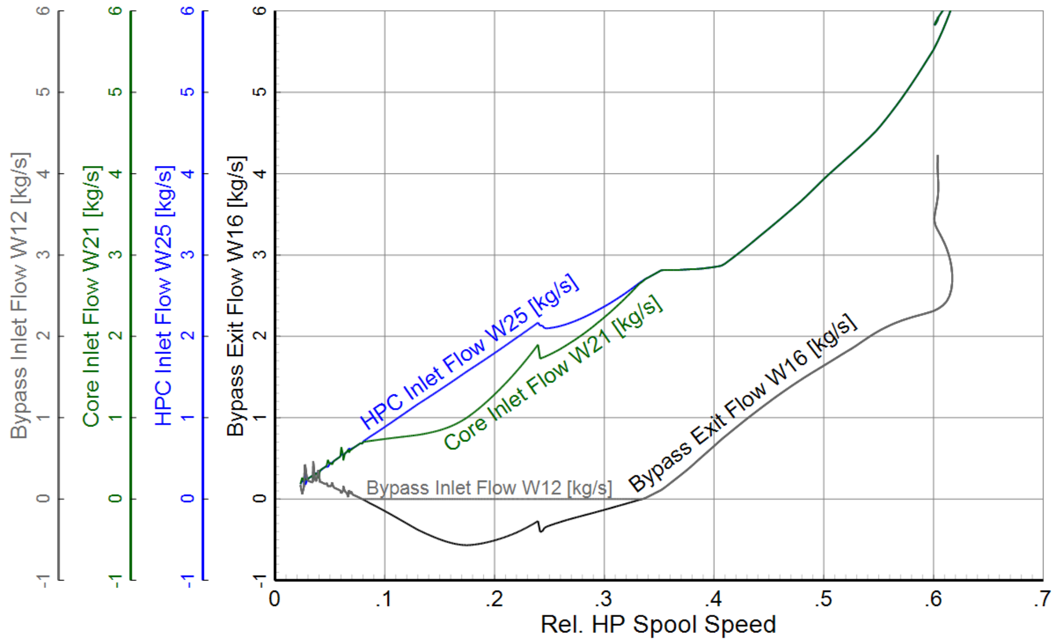
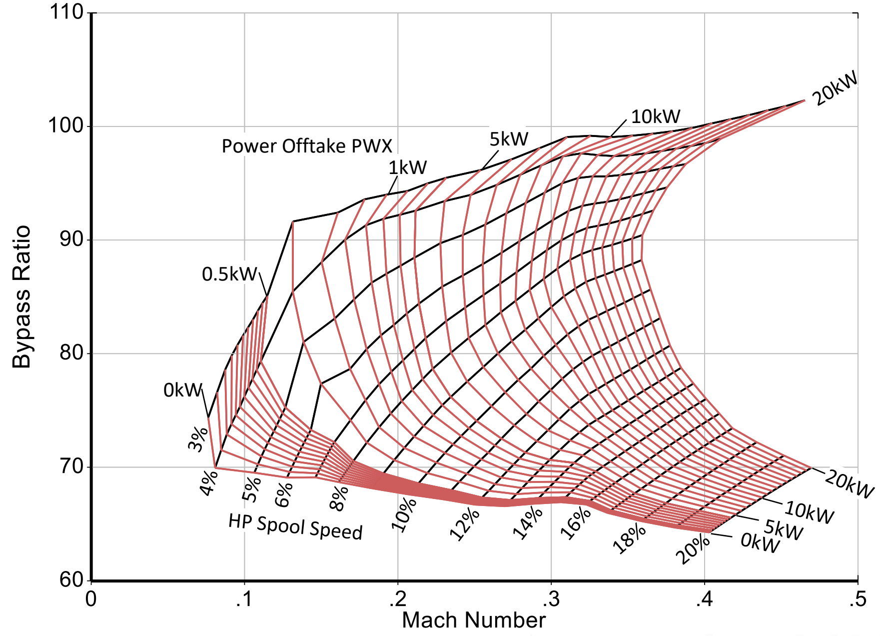
Two Interesting Starting and Windmilling Simulation Examples



During the start of a low-bypass ratio mixed-flow turbofan, it's possible that the high pressure compressor (HPC) will draw for some time more flow than the fan can deliver because its spool speed lags behind.



Windmilling of a high bypass ratio turbofan with power offtake from the gas generator.



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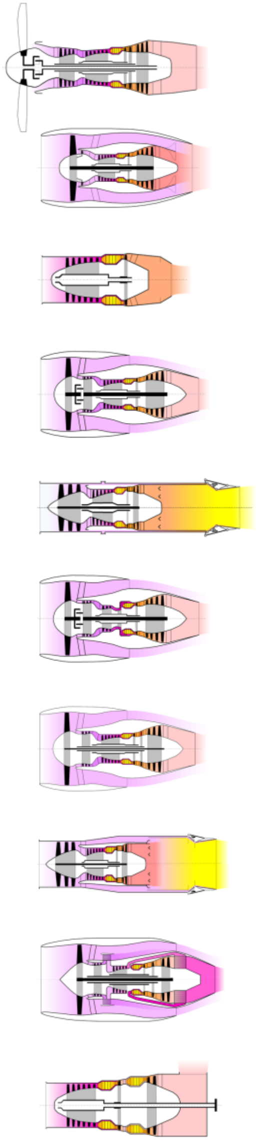

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Springer

Joachim Kurzke, Ian Halliwell, Robert Hill

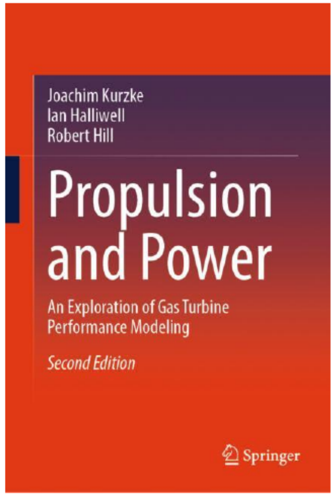
Propulsion and Power

An Exploration of Gas Turbine Performance Modeling

Guide for solving real world problems with modern computer software

Good text for teaching gas turbine design and performance

Solutions of overall system simulation problems



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