TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Teknik Eğitim Dökümanı

09-10.01.2023

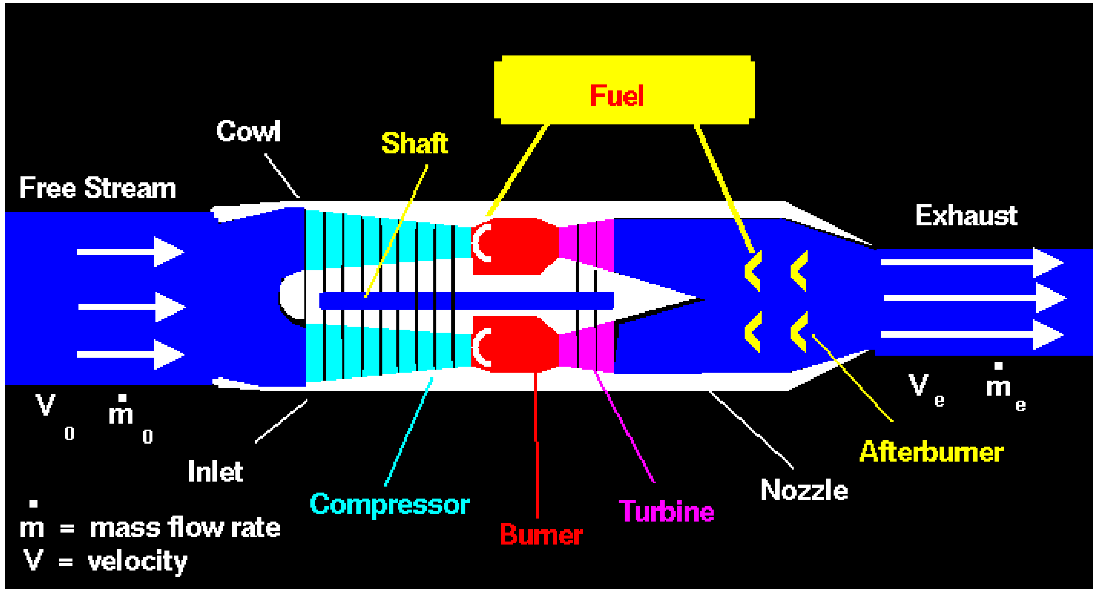
TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Aerodinamik Teknik Eğitim

09.01.2023

AFTERBURNERS – INTRODUCTORY CONCEPTS

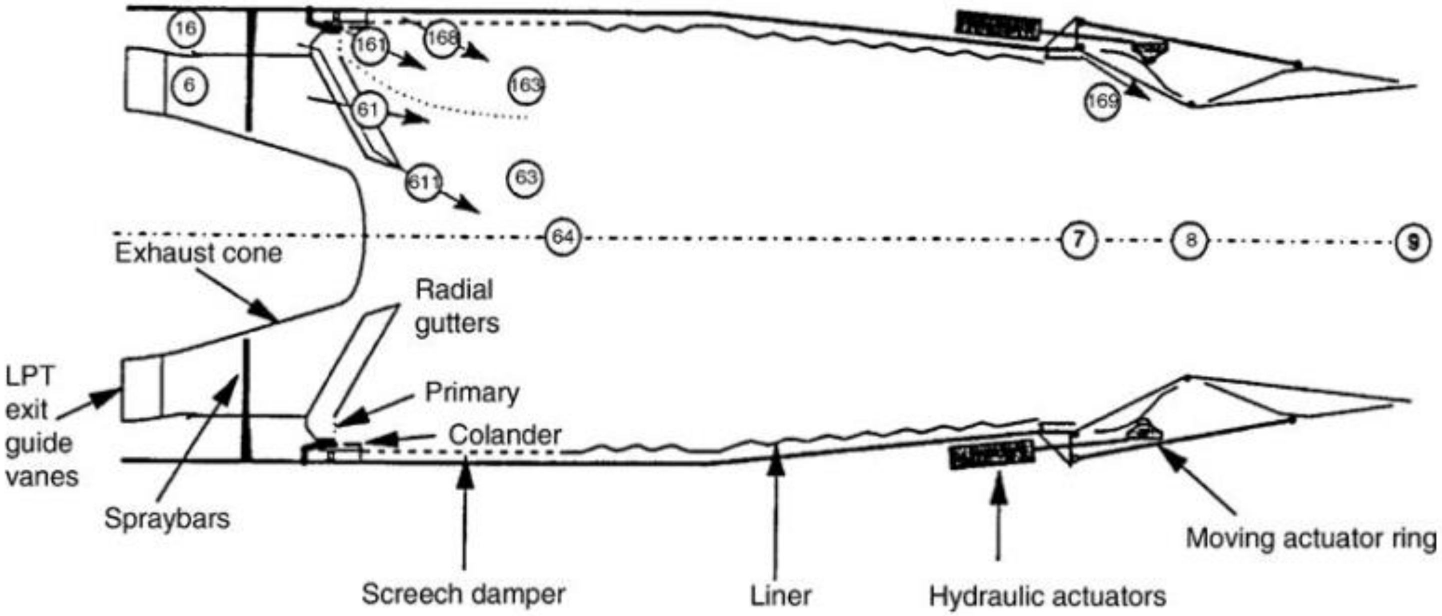
- Afterburners are used to produce more thrust while consuming a high amount of fuel.
- They are working for a short period of time for supersonic flight, combat and take-off.
- A schematic of a jet engine with an afterburner is shown below [1].
  - Afterburners are located between the turbine and exhaust nozzles.
  - They are comparably longer than the other parts of the jet engines.
- When they operate, the flame can be observed at the aft of the aircraft as shown in the EuroJet Typhoon aircraft below [2].
- If afterburners work, the operating mode refers as ‘wet’ operating mode while in the ‘dry’ operating mode combustion is not taking place in the afterburners.



$$\text{Thrust} = F = \dot{m}_e V_e - \dot{m}_0 V_0$$

AFTERBURNERS – INTRODUCTORY CONCEPTS

- Schematic of the afterburner parts are shown below [3].
- First components is the exhaust cone which also works as a diffuser to reduce the incoming gas velocity.
- The next part is the radial V-gutters. These gutters are the most crucial part of an afterburner for stable flame and operation.
- The third component is the fuel spray bars. As shown in the figure, fuel spray bars are not covered and injected the fuel particles directly to the afterburner.
- Reactions occur in a volume that is covered by liners. Thus, liners are needed to be cooled for longer operational time. Also, afterburner liners are used to damp potential combustion instabilities.
- The final part is the convergent divergent nozzle. For supersonic flight, the convergent and divergent nozzle areas can be changed by using actuators.



AFTERBURNERS – INTRODUCTORY CONCEPTS

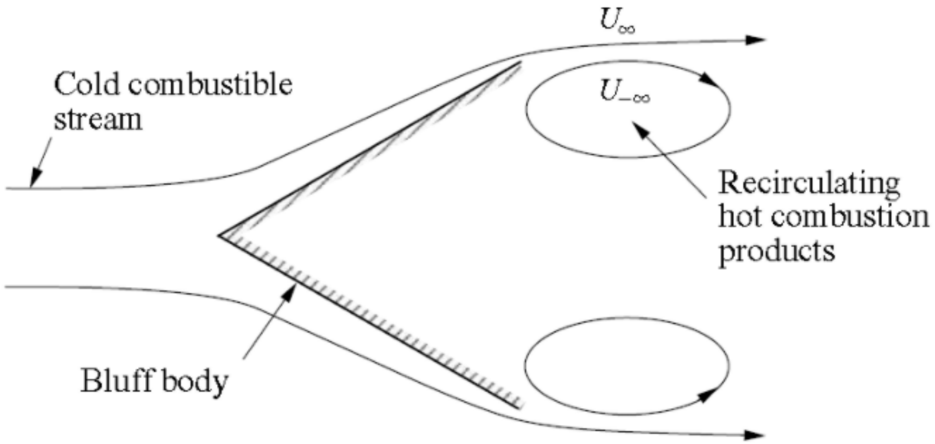
- Why do we need flame anchoring (stabilization)?
    - Propagation speed of the flame is lower than flow velocity
    - For fixed velocity: lower equivalence ratio → blow-off
    - For fixed equivalence ratio: higher velocity → blow-off
- Blow-off: Flame physically leaving the combustor
- Blow-off simply the function of combustor loading which is the ratio of chemical kinetic time to residence time.

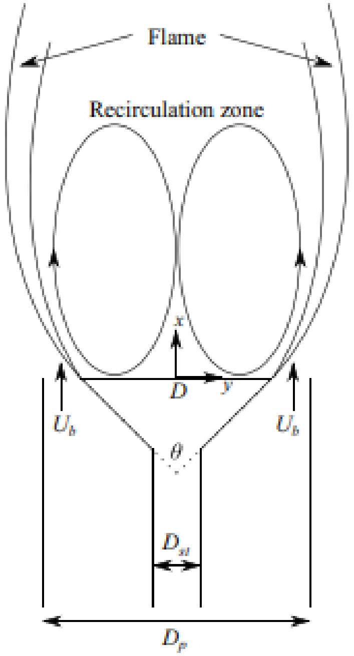
$$Loading = {}^{\tau_{che}}/_{\tau_{res}}$$

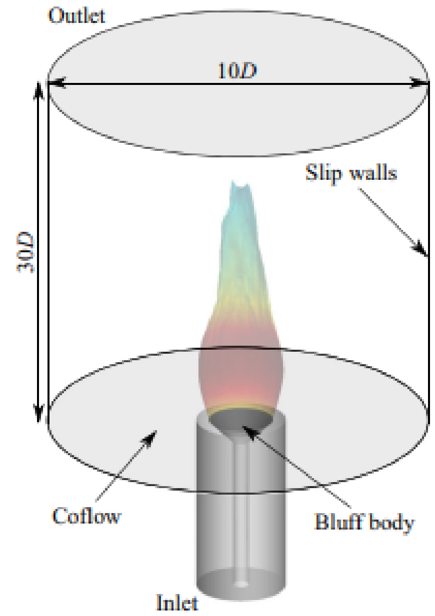
- Chemical kinetic time refers how much time requires for reaction
- Residence time characterizes the time which the reactants reside in the reaction zone
- If $\tau_{res} < \tau_{che} \xrightarrow{\hspace{2cm}}$ blow-off
- We need to increase the residence time or faster combustion to prevent blow-off.
- This is called as flame anchoring

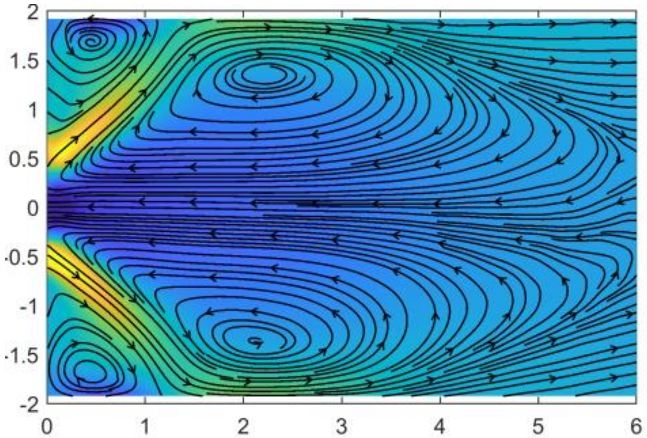
AFTERBURNERS – INTRODUCTORY CONCEPTS

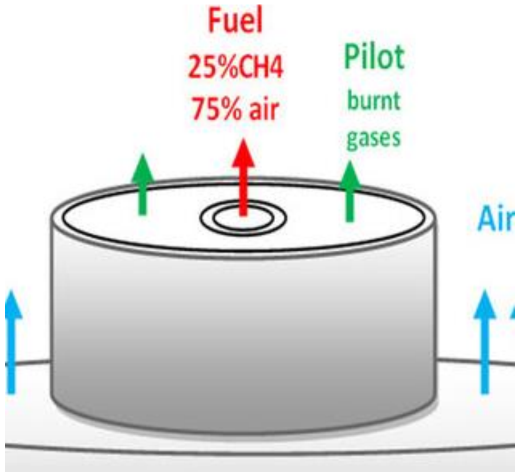
- Flame stabilization techniques:
  - Bluff body
  - Sudden expansion
  - Swirling flows
  - Piloted flames





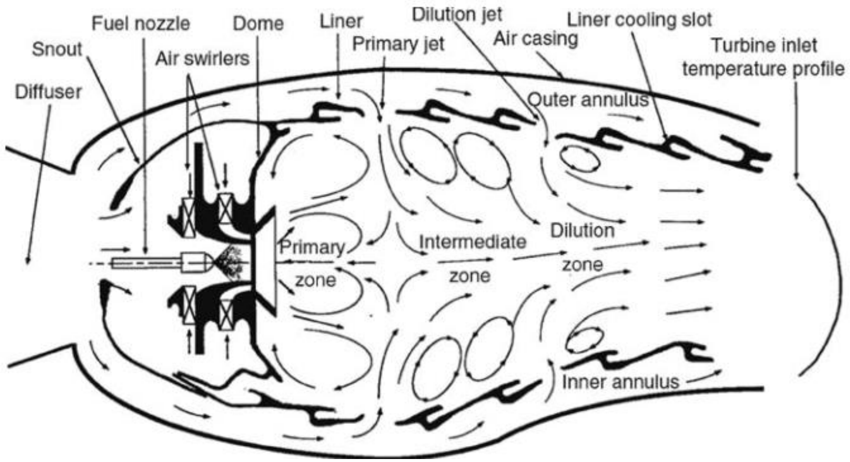




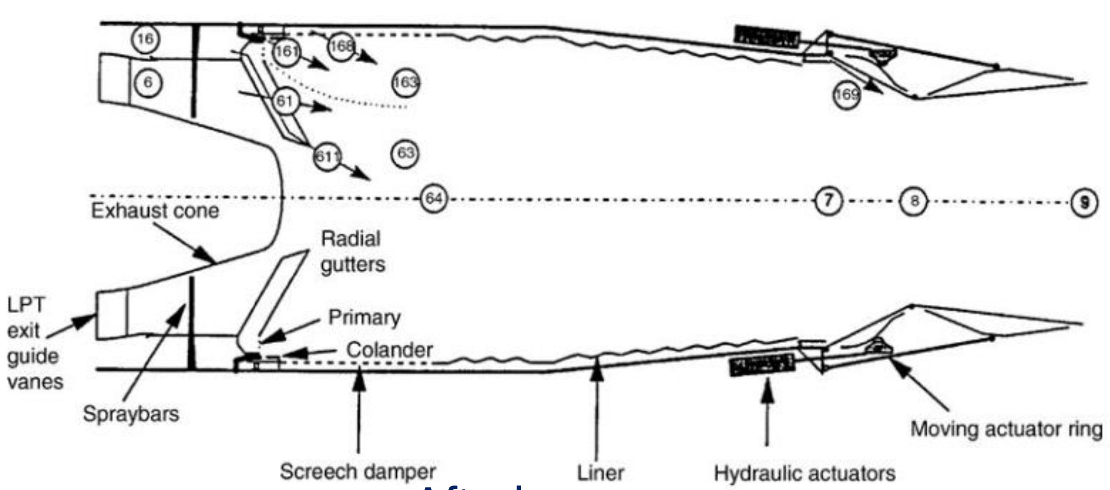


AFTERBURNERS – INTRODUCTORY CONCEPTS

- Before the details of the afterburner parts, a combustion chamber (burner) and afterburner is compared [3].
- Pure air composition enters the combustion chamber from the compressor, while burned gas composition flows inside the afterburner because reactions occurs in the combustion chamber.
- Flame stabilization is achived by air swirlers (generates swirl (tangential) velocity) in the combustion chamber which is a very efficient way to stabilize the flame. However, the swirl (tangential) velocity component is not favourable in the afterburner, thus the flame stabilize with V-gutters.
- The velocity in the combustion chamber is relatively slower than the afterburners. This provides easier ignition for combustion chambers.
- More complex fuel injectors are used in the combustors which provides smaller fuel particle size. But, the fuel injectors of the afterburners are very simple.
- Due to all reasons, lower combustion efficiency is observed in the afterburners.



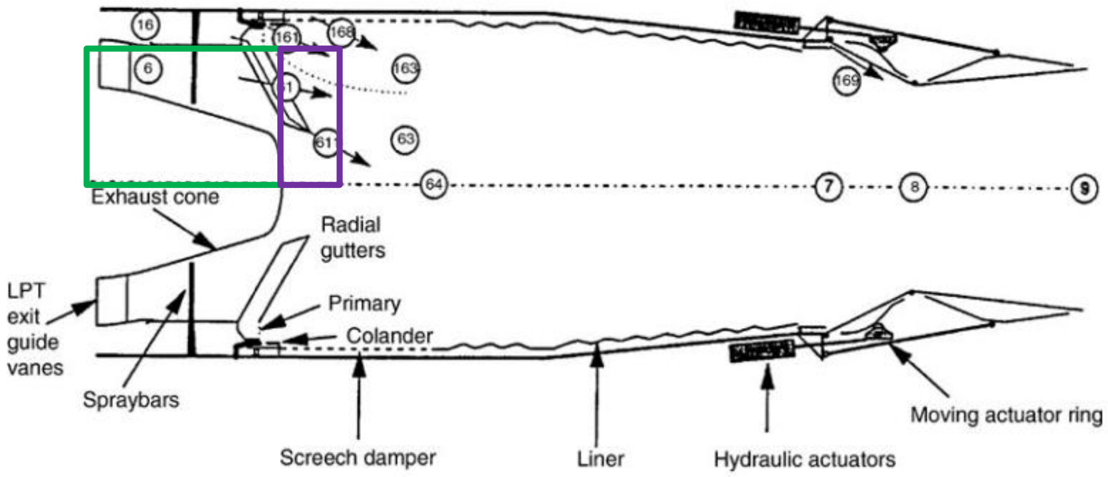
Combustion chamber

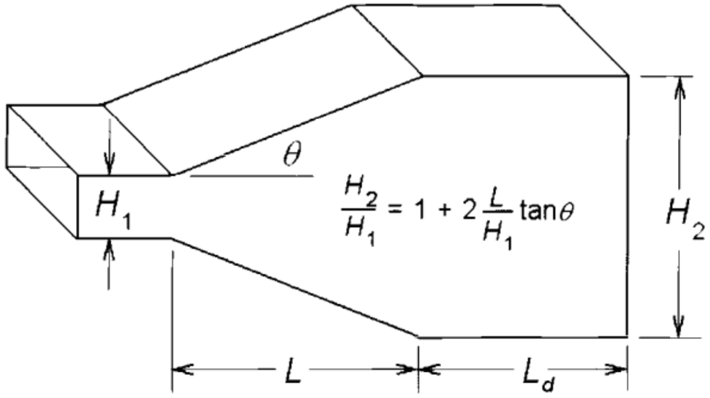


Afterburner

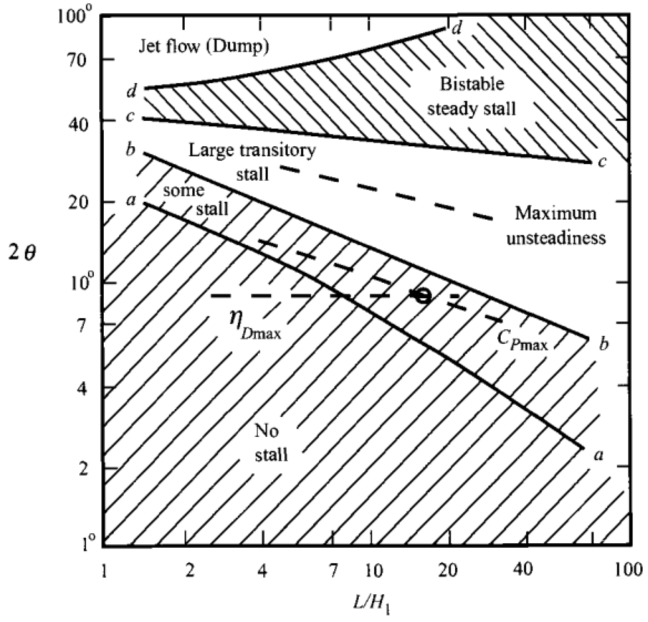
AFTERBURNERS – Components- Diffuser

- The exhaust cone section of the afterburner works as a kind of a diffuser.
- For stable combustion and easier ignition, the afterburner inlet velocity magnitude must be reduced.
- Exhaust cone consists of the two diffuser parts where the flow decreases gradually and suddenly.
- A diffuser must be designed as shorter as possible with minimum pressure loss.
- A typical planar diffuser with diffuser stability maps are shown below [4].
- If the diffuser is in the ‘No-Stall’ regime, it leads a relatively longer and heavier diffuser.
- If the diffuser angle is kept same and the design is shortened, the flow regime could change and an unstable diffuser could be observed.
- The diffuser should be designed regarding the stability and length issues.
- It must be noted that the type of diffuser is different than planar diffusers.
- Thus, generic stability curves must be investigated for annular diffusers and designs should based on these curves.





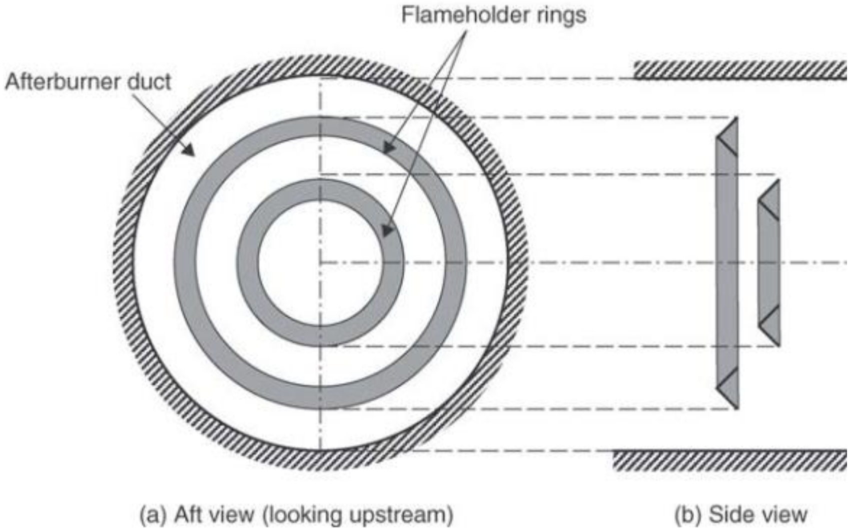
Diffuser



Diffuser stability Map

AFTERBURNERS – Components- V-Gutters

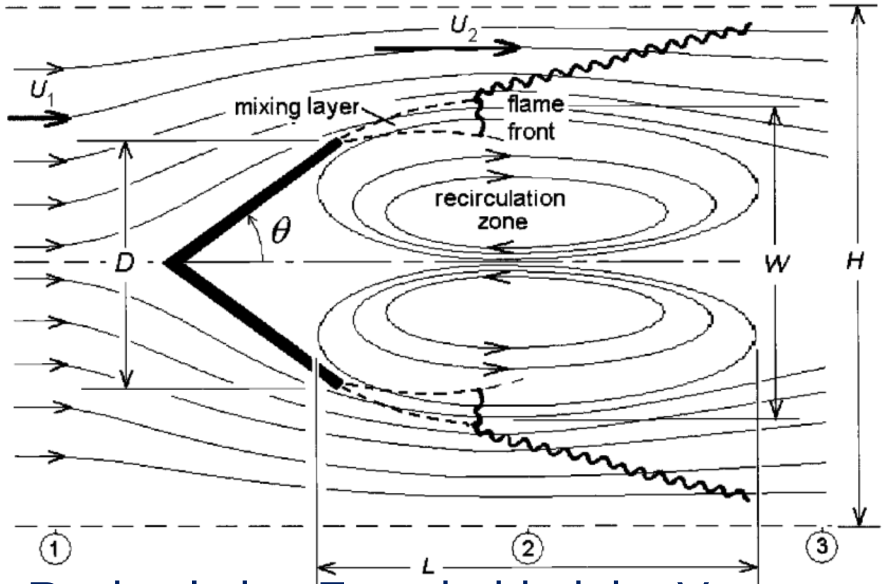
- In afterburners, the flame is mostly anchored by using V-gutters.
- A schematic of the V-gutter is shown below [3].
- After the V-gutter a recirculation zone (a flow reversal zone) occurs [4] which reduces the flow velocity, and provides easier ignition.
- Also, fuel particles returns into V-gutter in this reversal zone and stay longer in the reactiong zone which means that higher residence time (check Loading Formula).
- The incoming gas supplies the oxygen to the reaction zone and at a some point after the V-gutter a stading flame establishes.
- The flame propates through the afterburner and convergent-divergent nozzles, eventually.



(a) Aft view (looking upstream)

(b) Side view

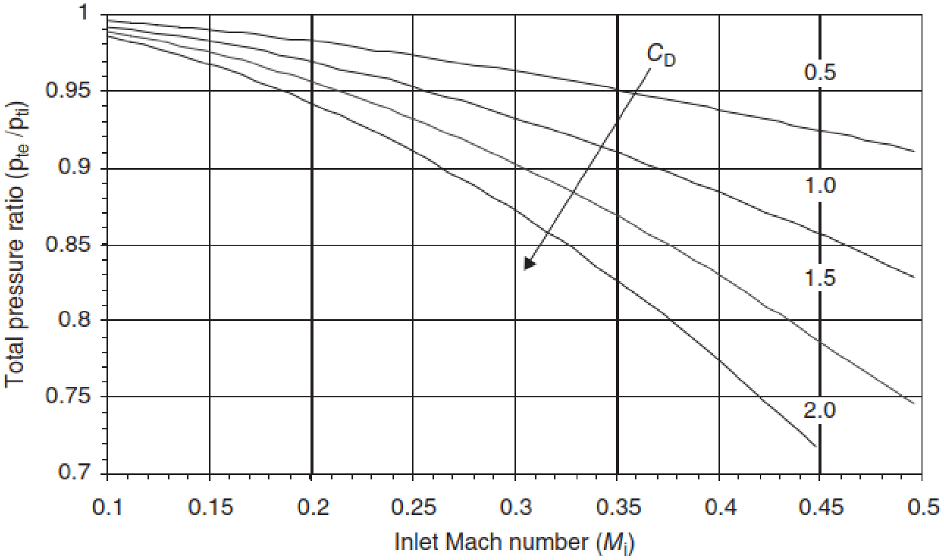
A schematic of the V-gutter

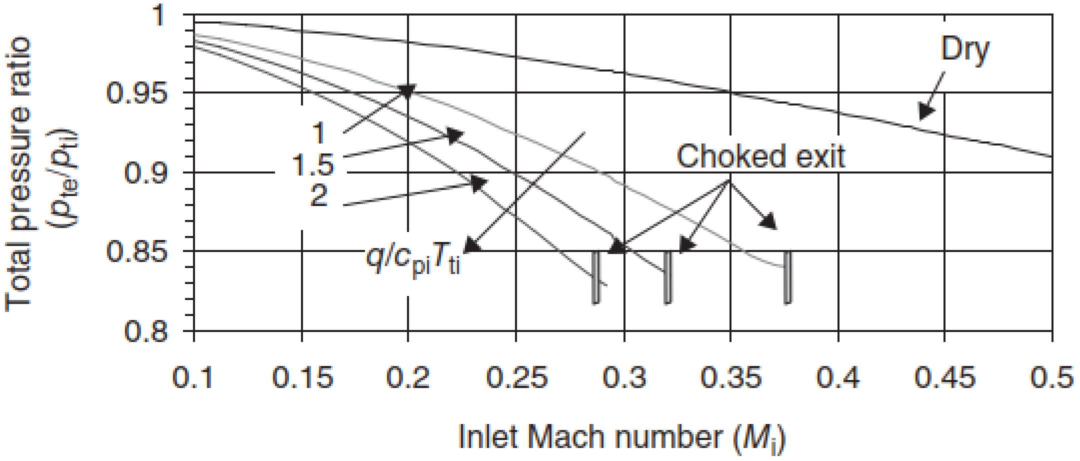


Recirculation Zone behind the V-gutter

AFTERBURNERS – Components- V-Gutters

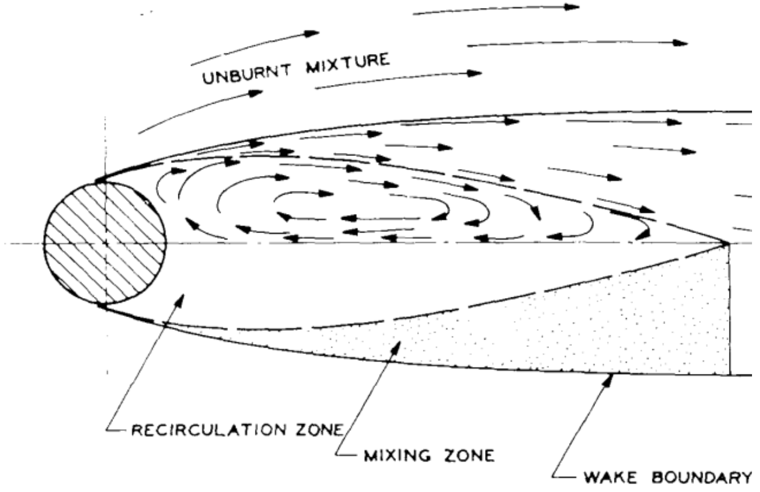
- One of the main issue of the V-gutters is to create blockage to the flow. If blockage is increased, it leads higher drag coefficient (Cd) and total pressure loss.
- A representative pressure loss due to V-gutters is shown below [3]. Participants must keep in their mind that, the V-gutters still exist in the dry condition. Thus, V-gutter design must have an optimal blockage value.
- In the wet mode, the total pressure drop is depending on the heat release $(\frac{q}{C_{pi} \cdot T_{ti}})$ in addition to inlet Mach number and drag coefficient. Also, blockage leads earlier choked flow (where Mach number equals 1, in appropriate wet conditions the Mach number must be 1 at the exit of the convergent nozzle rather than in the afterburner.) can be observed if the heat relase increases.
- Participants must be provided total pressure losses in dry and wet modes.

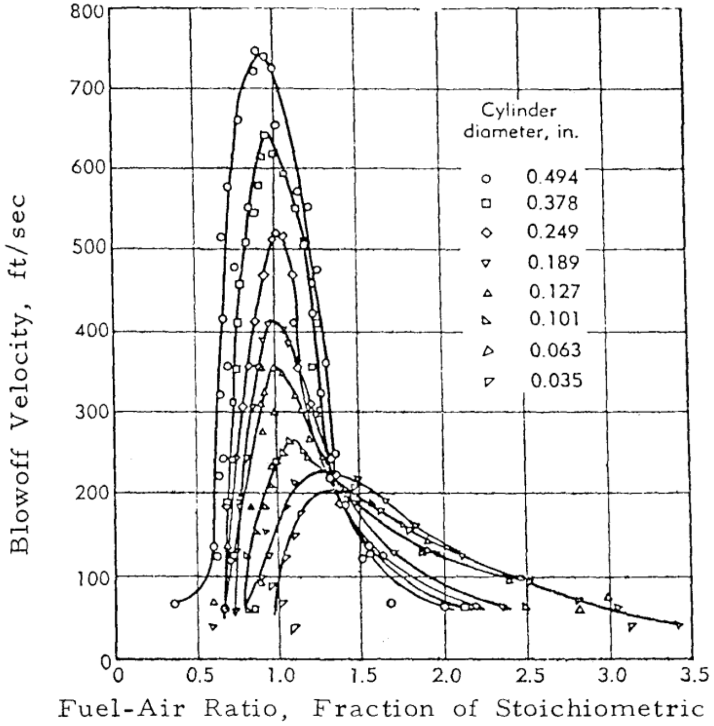

Afterburner total pressure loss
(dry mode)

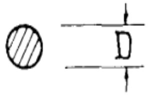

Afterburner total pressure loss
(wet mode)

AFTERBURNERS – Components- V-Gutters

- The size flame holder is directly related with the ignition and blowoff.
- Effect of the circular type flame holder dimension on the ignition and blowoff is shown below [6].
- Blowoff velocity means at what velocity magnitude the blowoff takes place.
- Lower ignition time also refers easier ignition.
- As shown in the plots, as the cylinder diameter increases, possibility of the blowoff decreases at specific fuel-air ratio levels. It also reduces ignition time. Even though, bigger flame holder leads higher drag coefficients.
- In this competition, **V-gutter design** is expected from participants. If participants indicate the pluses of V-gutters over other geometries, they will earn extra points.

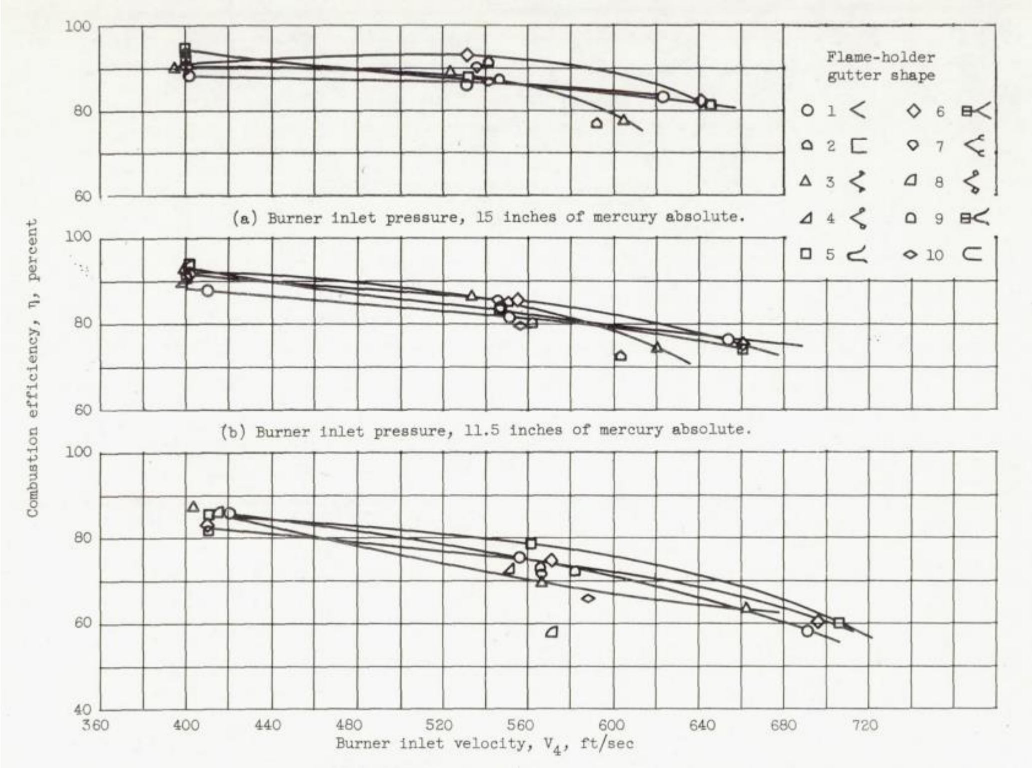




	Diameter [in]	Ignition Time x 10^{-4}
	1/8	3.09
	3/16	2.85
	1/4	2.8

AFTERBURNERS – Components- V-Gutters

- Resource books: 1- Aircraft Engine Design, details can be found in the References section
  2- Gas Turbine Combustion, Alternative Fuels and Emissions, Third Edition Arthur Lefevbre, Dilip R. Ballal
  3- Aircraft Propulsion, details can be found in the References section
  4- Elements of Propulsion, Gas Turbines and Rockets, 2nd Edition, Jack D. Mattingly and Keith M. Boyer
  5- Afterburners, details can be found in the References section
- In addition, NASA NTRS server has a lots of details about afterburners. For example, an experimental investigation of the various V-gutter shapes on the combustion efficiency is shown [7] below.
- In addition to resource books, using such experimental data will provide bonus points to the participants.



(a) Burner inlet pressure, 15 inches of mercury absolute.

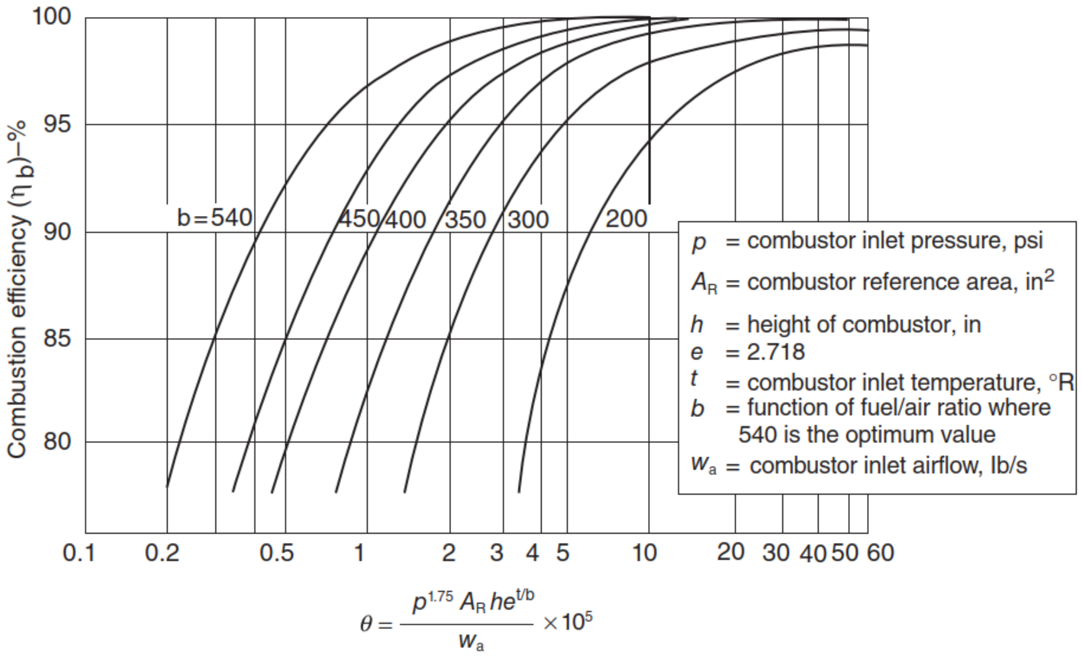
(b) Burner inlet pressure, 11.5 inches of mercury absolute.

AFTERBURNERS – Components- Liners

- The afterburner liners define the volume where the combustion takes place.
- If the combustor volume increases, combustor loading parameter increases and more efficient combustion occurs [3].
- The combustor loading parameter can be defined as:

$$CLP = \theta = \frac{p^{1.75}\, A_R\, h\, e^{\frac{t}{b}}}{\dot{m}}$$

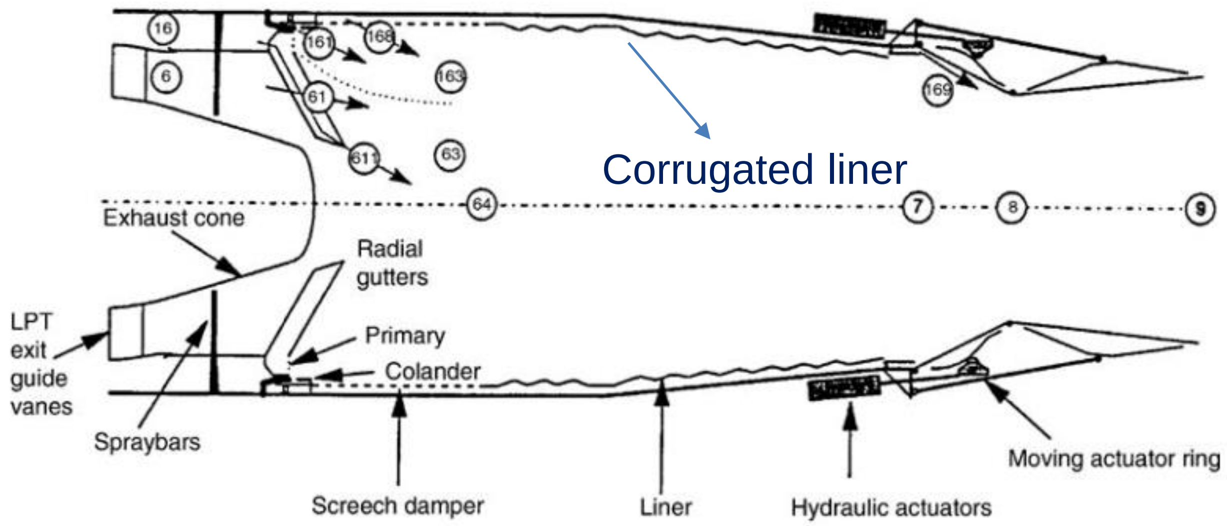
- p and t represents the afterburner intake pressure and temperature, respectively. $\dot{m}$ is the afterburner mass flow rate, A_R is the reference cross section area of the afterburner h is the radius of the afterburner.
- However, longer afterburner requires more coolant mass flow rate and it makes heavier afterburner which is not prefereably.

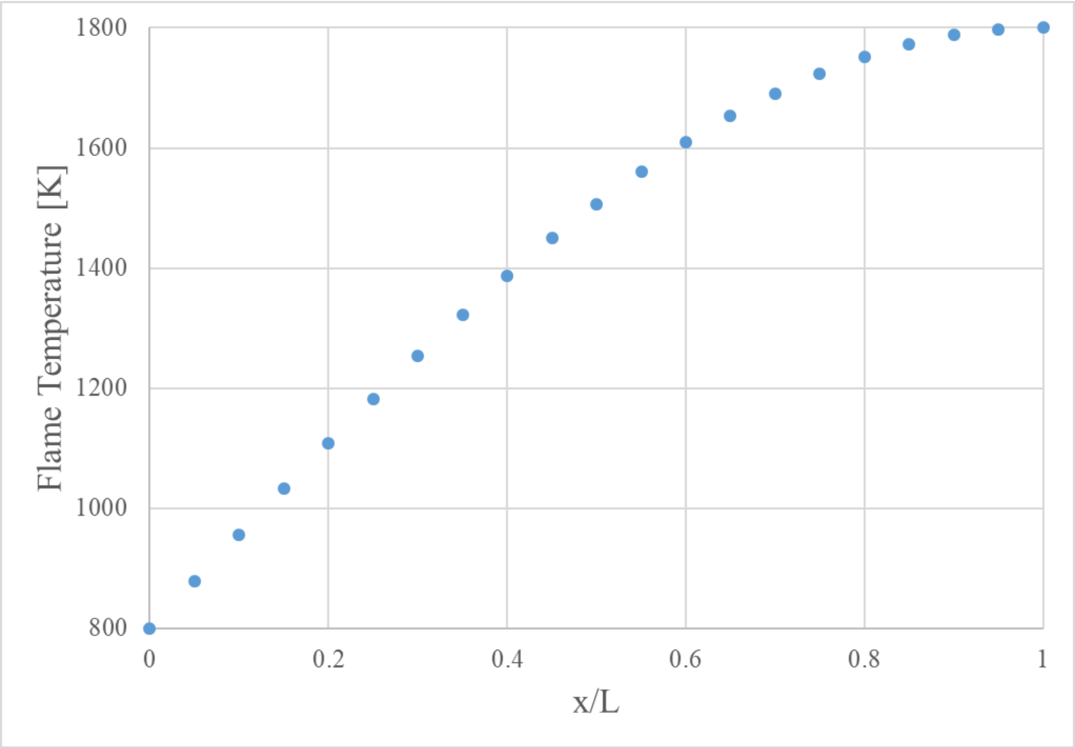


AFTERBURNERS – Components- Liners

- Afterburner liners have a corrugated shape for mechanical and aerodynamic purposes and a schematic of the afterburner with a corrugated liner is shown below [2].
- Participants should investigate and report why a corrugated liner is necessary for afterburners.
- For cooling design and weight analysis, participants can treat the liner as a straight liner.
- Flame tempeature distribution inside the afterburner can be obtained as shown below [8]. The x represents the axial position after the v gutter, 0 is the inlet condition and L is the exit of the afterburner. If the afterburner exit temperature 1800 K and the inlet temperature 800 K, you will be obtained a flame temperature distribution as:

$$\frac{T_{g,x-}T_{g,0}}{T_{g,L-}T_{g,0}} = \sin\frac{\pi}{2}\frac{x}{L}$$





AFTERBURNERS – Components- Liners

- Resource books: 1- Aircraft Engine Design, details can be found in the References section
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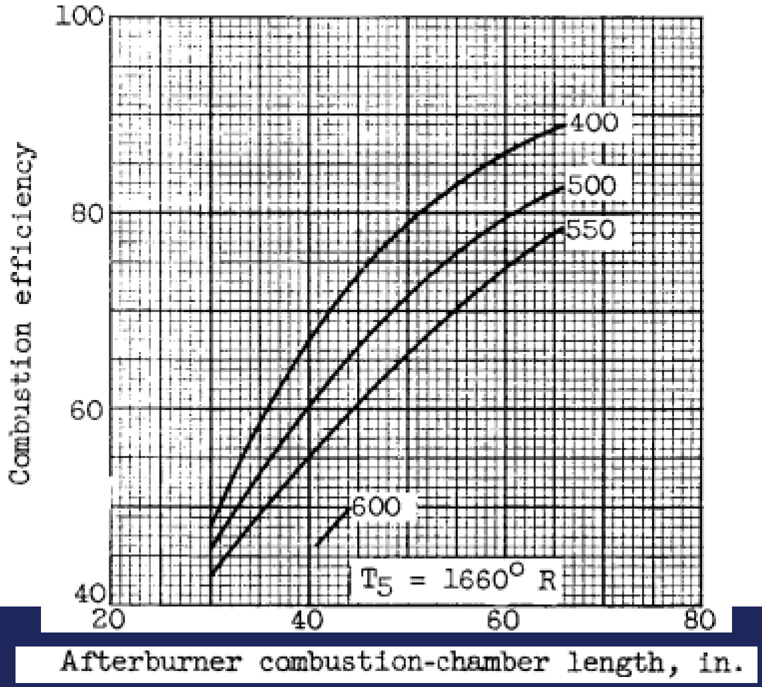
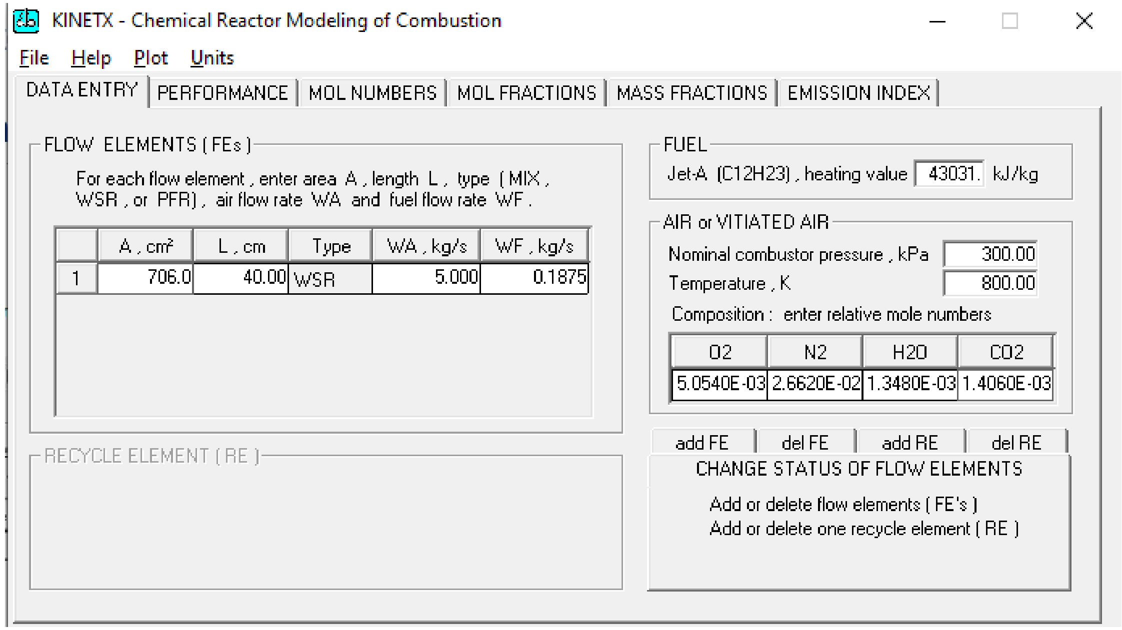
  5- Afterburners, details can be found in the References section
- In addition, NASA NTRS server has a lots of details about afterburners. For example, an experimental investigation of the effect of the afterburner length on the combustion efficiency is shown [5] below. It is obviosly seen that, the longer afterburner leads higher combustion efficiency.
- Also, the white boxes represents the inlet velocity in ft/s unit. As the inlet velocity decreases, the combustion efficiency will increase.
- In addition to resource books, using such experimental data will provide bonus points to the participants.



Tools

- The AEDsys software provided by Aircraft Engine Design Book has a chemical reactor network modeling solver called KINETX. You can obtain the software by downloading Supplemental Materials at this link: https://arc.aiaa.org/doi/book/10.2514/4.105173
- This solver can be used for the initial sizing.
- Participants can enter the cross section area, length, gas and fuel flow rate, inlet pressure and temperatuer values and the gas composition.
- For given dimensions and boundary conditions, 1800 K is obtained at the exit of the afterburner with a combustion efficiency of 88.1%.
- Participants should compare the results with experimental data from the provided resources and NASA documents.
- Also, participants should provide **brief** information about types of flow element, WSR and EQL (Chemical Equilibrium), in their reports.



For each flow element , enter area A , length L , type (MIX , WSR , or PFR) , air flow rate WA and fuel flow rate WF .

	A , cm²	L , cm	Type	WA , kg/s	WF , kg/s
1	706.0	40.00	WSR	5.000	0.1875

Jet-A (C12H23) , heating value 43031. kJ/kg

Nominal combustor pressure , kPa 300.00

Temperature , K 800.00

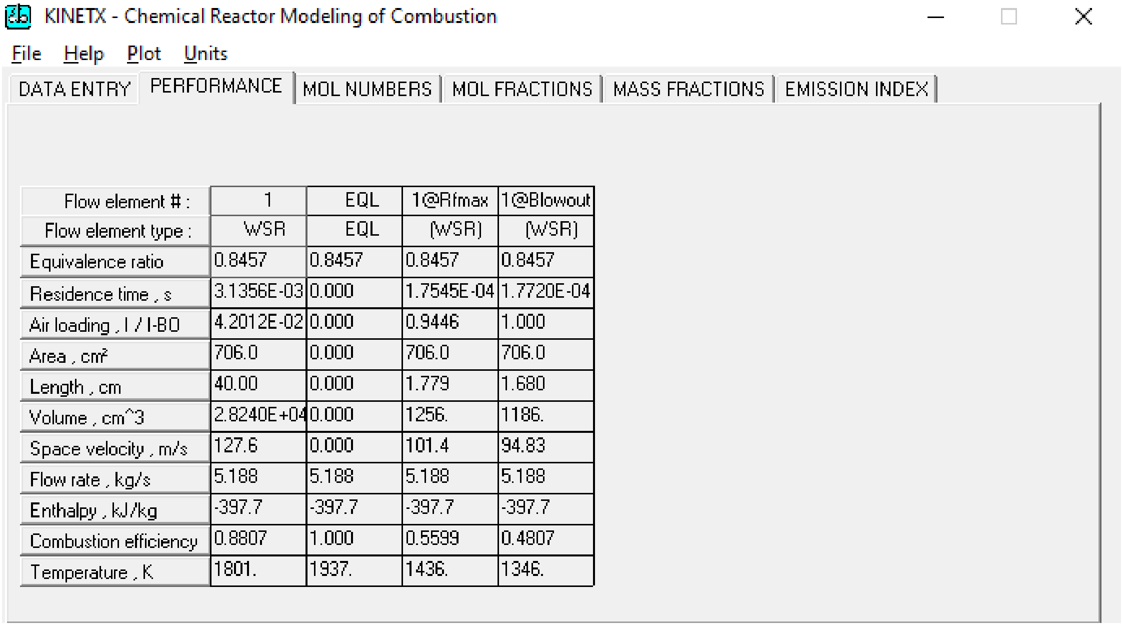
Composition : enter relative mole numbers

O2	N2	H2O	CO2
5.0540E-03	2.6620E-02	1.3480E-03	1.4060E-03

CHANGE STATUS OF FLOW ELEMENTS

Add or delete flow elements (FE's)

Add or delete one recycle element (RE)



Flow element # :	1	EQL	1@Rfmax	1@Blowout
Flow element type :	WSR	EQL	(WSR)	(WSR)
Equivalence ratio	0.8457	0.8457	0.8457	0.8457
Residence time , s	3.1356E-03	0.000	1.7545E-04	1.7720E-04
Air loading , I / I-BO	4.2012E-02	0.000	0.9446	1.000
Area , cm²	706.0	0.000	706.0	706.0
Length , cm	40.00	0.000	1.779	1.680
Volume , cm^3	2.8240E+04	0.000	1256.	1186.
Space velocity , m/s	127.6	0.000	101.4	94.83
Flow rate , kg/s	5.188	5.188	5.188	5.188
Enthalpy , kJ/kg	-397.7	-397.7	-397.7	-397.7
Combustion efficiency	0.8807	1.000	0.5599	0.4807
Temperature , K	1801.	1937.	1436.	1346.

DTR Aşaması

- Bir sonraki aşamada katılımcılardan tasarımlarını nümerik analizlerle değerlendirmeleri beklenmektedir.
- Bu amaçla katılımcılardan 2 boyutlu reaktif nümerik analizler beklenmektedir.
- 3 boyutlu yapılacak analizler ise kullanıcılara bonus puan getirecektir.
- Kullanıcılar istedikleri yazılımı kullanma konusunda özgürdürler. Kullanıcıların ANSYS Fluent, CFX ve Star CCM yazılımları konusunda soruları olursa cevaplanacaktır.
- Kullanıcılardan beklenen tasarladıkları difüzör, V-gutter ve çıkış lülesinin bekledikleri performanslarını detaylı bir şekilde sunup KTR aşamasındaki tasarımlarına ne kadar yakın sonuçlar elde ettiklerini göstermeleridir.
- Ayrıca bu eğitim sonunda tasarımlar değişecekse bunlar DTR raporuna yansıtılacak olup nümerik analizler yeni tasarımla kıyaslanacaktır.
- Kullanıcılar yaptıkları analizlerde kullandıkları şemaları, modelleri ve derecelerini raporlandırmalıdırlar.

Reynolds Ortalamalı Navier Stokes Denklemleri

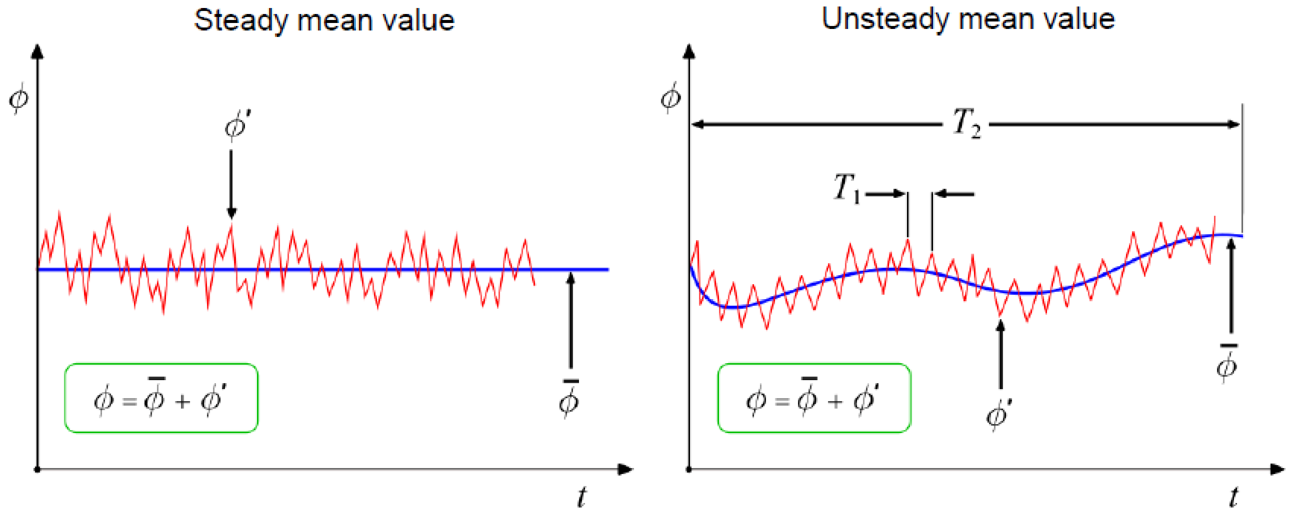
- İlk olarak Navier-Stokes denklemlerini ele alalım.
- İlk denklem süreklilik denklemini ifade etmektedir. Yani kütlenin korunumudur.
- İkinci denkelm ise momentum korunumunu ifade etmektedir.

$$\nabla \cdot (\mathbf{u}) = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = \frac{-\nabla p}{\rho} + \nu \nabla^2 \mathbf{u}$$

Reynolds Ortalamalı Navier Stokes Denklemleri

- Türbülanslı akışlar hız, basınç ve diğer tüm bileşenlerin salınmasını içermektedir.
- Salınımların ya da küçük ölçeklerin eddylerin modellenmesi için iki ortalama türü sıklıkla kullanılmaktadır:
  - Reynolds Ortalaması
  - Filtreleme
- Bu iki yöntemin kullanılması da ek terimler getirmektedir ve “kapanma” problem oluşturmaktadır.



$$\phi(\mathbf{x},t) = \underbrace{\bar{\phi}(\mathbf{x})}_{mean\ value} + \underbrace{\phi'(\mathbf{x},t)}_{fluctuating\ part}$$

$$\phi(\mathbf{x},t) = \underbrace{\bar{\phi}(\mathbf{x},t)}_{mean\ value} + \underbrace{\phi'(\mathbf{x},t)}_{fluctuating\ part}$$

Filter function

$$\tilde{\mathbf{u}}(\mathbf{x},t) = \int G(r,\mathbf{x})\mathbf{u}(\mathbf{x}-r,t)dr$$

$$\bar{\phi}(\mathbf{x}) = \lim_{T\to+\infty}\frac{1}{T}\int_t^{t+T}\phi(\mathbf{x},t)\,\mathrm{d}t$$ where $$\phi(\mathbf{x},t) = \bar{\phi}(\mathbf{x}) + \phi'(\mathbf{x},t)$$

$$\mathbf{u}'(\mathbf{x},t) = \mathbf{u}(\mathbf{x},t) - \tilde{\mathbf{u}}(\mathbf{x},t)$$

Reynolds Ortalamalı Navier Stokes Denklemleri

Navier-Stokes Denklemleri

$$\nabla \cdot (\mathbf{u}) = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = \frac{-\nabla p}{\rho} + \nu \nabla^2 \mathbf{u}$$

$$\phi(\mathbf{x},t) = \bar{\phi}(\mathbf{x},t) + \phi'(\mathbf{x},t) \quad \bar{\phi}' = 0, \qquad \overline{\phi'^2} \neq 0, \quad \overline{\phi'\varphi'} \neq 0.$$

Reynolds Ortalamalı Navier Stokes Denklemleri

$$\mathbf{u}(\mathbf{x},t) = \bar{\mathbf{u}}(\mathbf{x}) + \mathbf{u}'(\mathbf{x},t),$$
$$p(\mathbf{x},t) = \bar{p}(\mathbf{x}) + p'(\mathbf{x},t)$$

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}\bar{\mathbf{u}}) = \frac{-\nabla \bar{p}}{\rho} + \nu \nabla^2 \bar{\mathbf{u}} - \frac{1}{\rho} \nabla \cdot \tau^R$$

$$\tau^R = -\rho\left(\overline{\mathbf{u}'\mathbf{u}'}\right) = -\begin{pmatrix} \rho\overline{u'u'} & \rho\overline{u'v'} & \rho\overline{u'w'} \\ \rho\overline{v'u'} & \rho\overline{v'v'} & \rho\overline{v'w'} \\ \rho\overline{w'u'} & \rho\overline{w'v'} & \rho\overline{w'w'} \end{pmatrix}$$

Reynolds Ortalamalı Navier Stokes Denklemleri

- Reynolds stress tensörünü modellemek için Boussinesq varsayımı sıklıkla kullanılır.
- Bu varsayımda Reynolds Stress Tensörü ortalama hız gradyanı ile ilişkilendirilir.
- D strain rate tensorunu
- $\mu_T$türbülans viskozitesini
- I identity vector u gösterir
- Buradaki amaç türbülans vizkozitesini modellemektedir. Türbülans modelleri türbülans vizkozitesini modellemek için farklı yaklaşımlar göstermektedir
- DTR aşamasında katılımcılar kullandıkları türbülans modelini neden seçtiklerini ve türbülans modelinde terimlerin ne anlama geldiğini **kısaca** anlatmalıdır.

$$\tau^R = -\rho\left(\overline{\mathbf{u}'\mathbf{u}'}\right) = 2\mu_T\overline{\mathbf{D}}^R - \frac{2}{3}\rho k\mathbf{I} = \mu_T\left[\nabla\overline{\mathbf{u}} + \left(\nabla\overline{\mathbf{u}}\right)^{\mathrm{T}}\right] - \frac{2}{3}\rho k\mathbf{I}$$

$$\mu_t = C_\mu \frac{k^2}{\varepsilon}$$

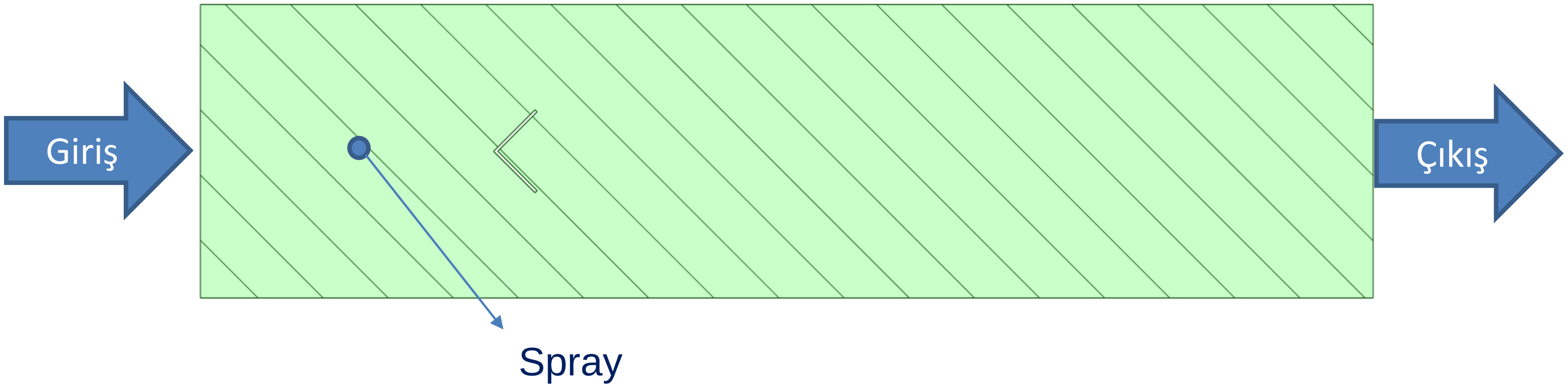
$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij}E_{ij} - \rho\varepsilon$$

For dissipation ε[4]

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

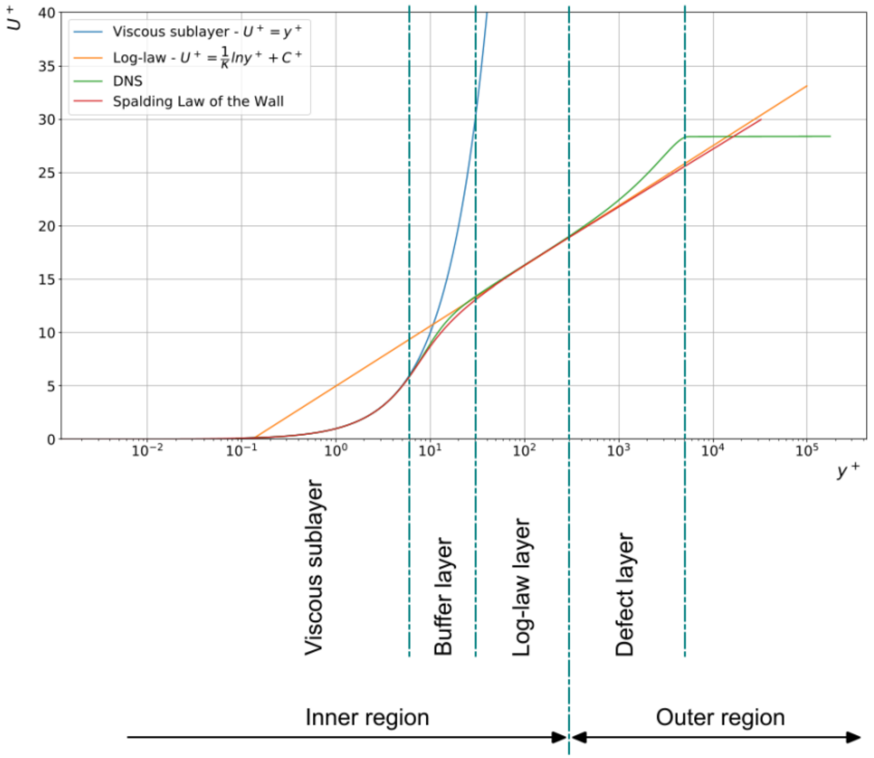
Örnek Problem

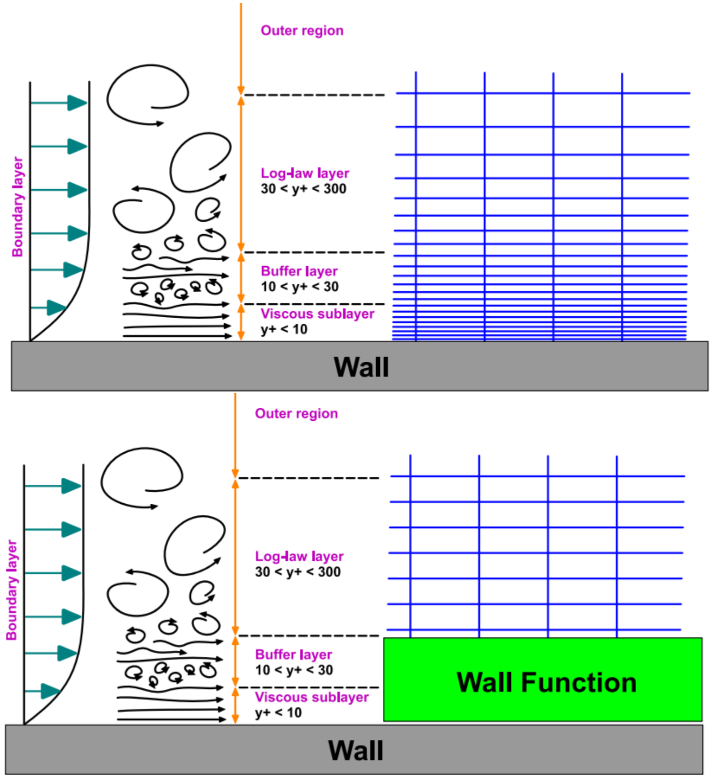
- Bir V-gutter etrafındaki reaktif akış aşağıdaki gibi görülmektedir.
- Bu problemde spray, reaksiyon, türbülans modellenmiş olup karışık bir mühendislik probleminin nümerik olarak nasıl modelleneceğine dair katılımcılara yol gösterecektir.

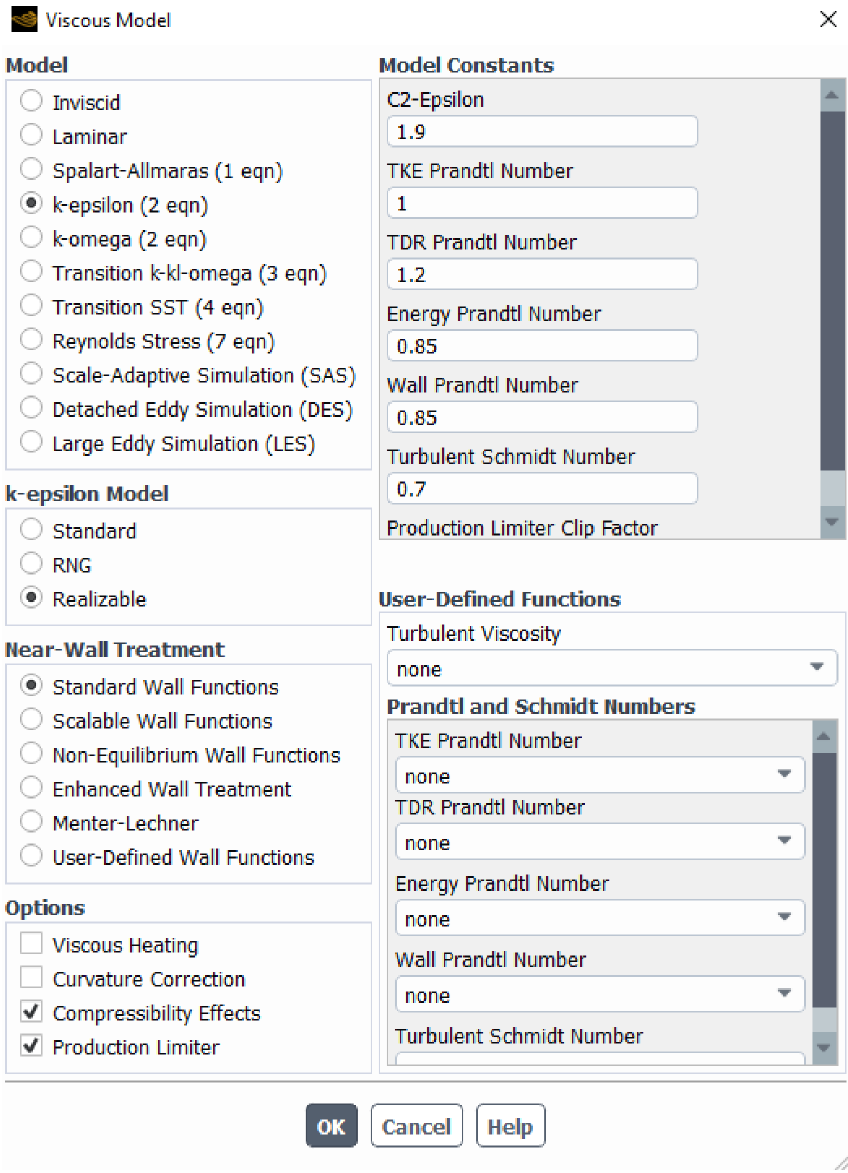


Türbülans Modelleme

- Katılımcıların 2 denklemli türbülans modellerinden birini kullanmaları tavsiye edilmektedir.
- Eğer katılımcılar duvar dibindeki ağ yapısını daha sık oluşturacaklarsa k-omega tabanlı bir türbülans modelini, daha seyrek bir ağ yapısıyla geçeceklerse k-epsilon tabanlı bir türbülans modeli kullanmaları tavsiye edilmektedir.
- Fakat, duvar dibindeki ağ yapısını daha sık yapıp k-epsilon tabanlı bir türbülans modeli kullanmayı tercih edeceklerse duvar fonksiyonunu buna göre seçmelidirler.






Viscous Model

Model

- ○ Inviscid
- ○ Laminar
- ○ Spalart-Allmaras (1 eqn)
- ● k-epsilon (2 eqn)
- ○ k-omega (2 eqn)
- ○ Transition k-kl-omega (3 eqn)
- ○ Transition SST (4 eqn)
- ○ Reynolds Stress (7 eqn)
- ○ Scale-Adaptive Simulation (SAS)
- ○ Detached Eddy Simulation (DES)
- ○ Large Eddy Simulation (LES)

k-epsilon Model

- ○ Standard
- ○ RNG
- ● Realizable

Near-Wall Treatment

- ● Standard Wall Functions
- ○ Scalable Wall Functions
- ○ Non-Equilibrium Wall Functions
- ○ Enhanced Wall Treatment
- ○ Menter-Lechner
- ○ User-Defined Wall Functions

Options

- ☐ Viscous Heating
- ☐ Curvature Correction
- ☑ Compressibility Effects
- ☑ Production Limiter

Model Constants

C2-Epsilon: 1.9
TKE Prandtl Number: 1
TDR Prandtl Number: 1.2
Energy Prandtl Number: 0.85
Wall Prandtl Number: 0.85
Turbulent Schmidt Number: 0.7
Production Limiter Clip Factor

User-Defined Functions

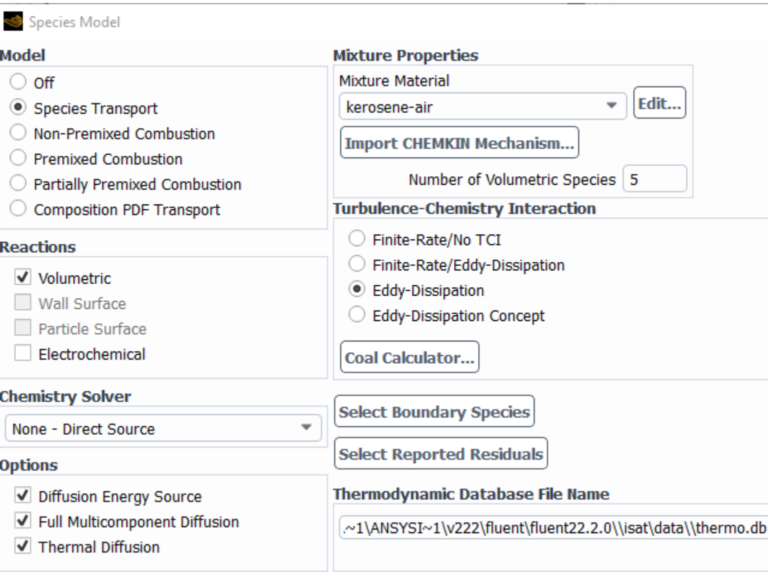
Turbulent Viscosity: none

Prandtl and Schmidt Numbers

TKE Prandtl Number: none
TDR Prandtl Number: none
Energy Prandtl Number: none
Wall Prandtl Number: none
Turbulent Schmidt Number

Reaksiyon Modelleme

- Katılımcılardan bu aşamada beklenen yanma modeli ‘Species Transport’ modelini kullanmalarıdır. Eğer kullanıcılar farklı bir yanma modeli kullanmayı tercih ediyorlarsa sebeplerini açıklamalıdır.
- Art yakıcılarda akış yanma odalarının aksine hızlıdır. Yani akış sıkıştırılabilir rejimdedir. Malzeme özelliklerinden sıkıştırılabilirliği göz önüne olacak bir yoğunluk modeli seçilmelidir.
- Son olarak kullanılan reaksiyon modeli aşağıda gözükmektedir. Tek bir denklemli yanma modeli olup kerosen’in en basit yanmasını içermektedir. Bu aşamada katılımcıların daha fazla sayıda denklem kullanması teşvik edilip bonus puan verilecektir.



Species Model

Model

○ Off
● Species Transport
○ Non-Premixed Combustion
○ Premixed Combustion
○ Partially Premixed Combustion
○ Composition PDF Transport

Reactions

☑ Volumetric
☐ Wall Surface
☐ Particle Surface
☐ Electrochemical

Chemistry Solver

None - Direct Source

Options

☑ Diffusion Energy Source
☑ Full Multicomponent Diffusion
☑ Thermal Diffusion

Mixture Properties

Mixture Material: kerosene-air

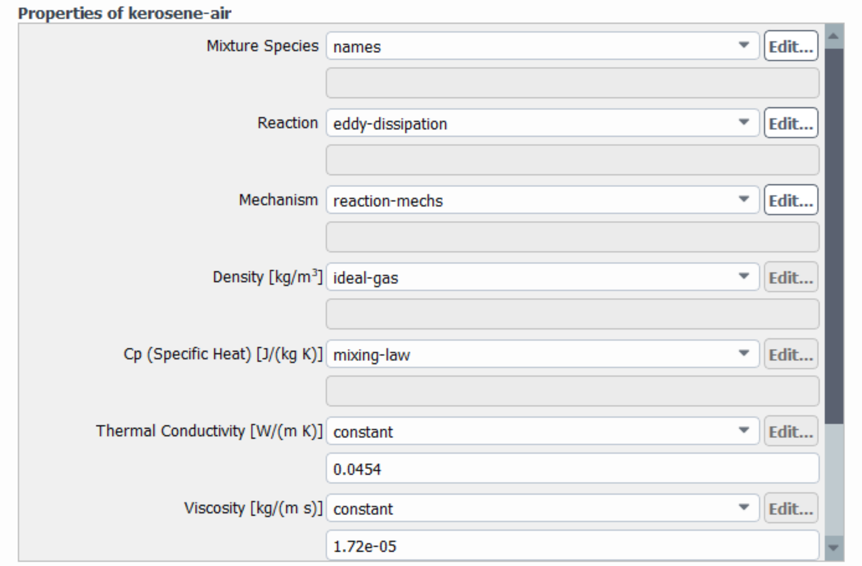
Number of Volumetric Species: 5

Turbulence-Chemistry Interaction

○ Finite-Rate/No TCI
○ Finite-Rate/Eddy-Dissipation
● Eddy-Dissipation
○ Eddy-Dissipation Concept

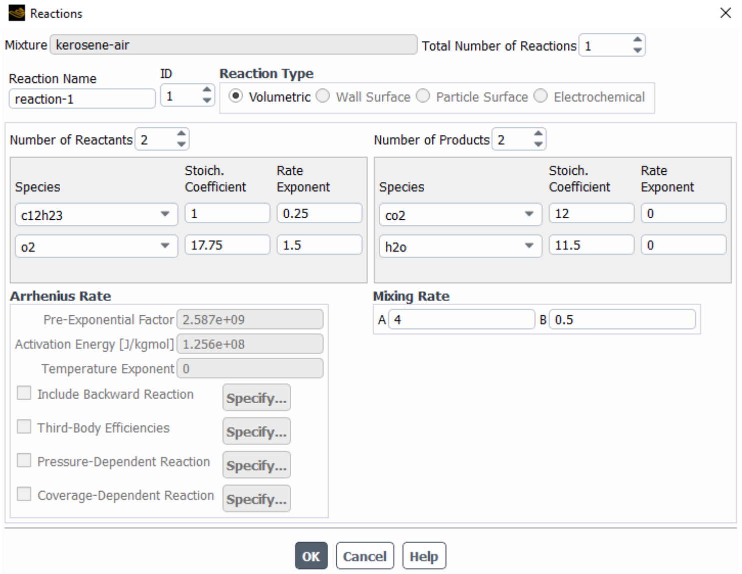
Thermodynamic Database File Name

.~1\ANSYSI~1\v222\fluent\fluent22.2.0\\isat\data\\thermo.db



Properties of kerosene-air

Mixture Species	names
Reaction	eddy-dissipation
Mechanism	reaction-mechs
Density [kg/m^3]	ideal-gas
Cp (Specific Heat) [J/(kg K)]	mixing-law
Thermal Conductivity [W/(m K)]	constant 0.0454
Viscosity [kg/(m s)]	constant 1.72e-05



Reactions

Mixture: kerosene-air
Total Number of Reactions: 1

Reaction Name: reaction-1
ID: 1

Reaction Type

● Volumetric ○ Wall Surface ○ Particle Surface ○ Electrochemical

Number of Reactants: 2

Species	Stoich. Coefficient	Rate Exponent
c12h23	1	0.25
o2	17.75	1.5

Number of Products: 2

Species	Stoich. Coefficient	Rate Exponent
co2	12	0
h2o	11.5	0

Arrhenius Rate

Pre-Exponential Factor: 2.587e+09
Activation Energy [J/kgmol]: 1.256e+08
Temperature Exponent: 0

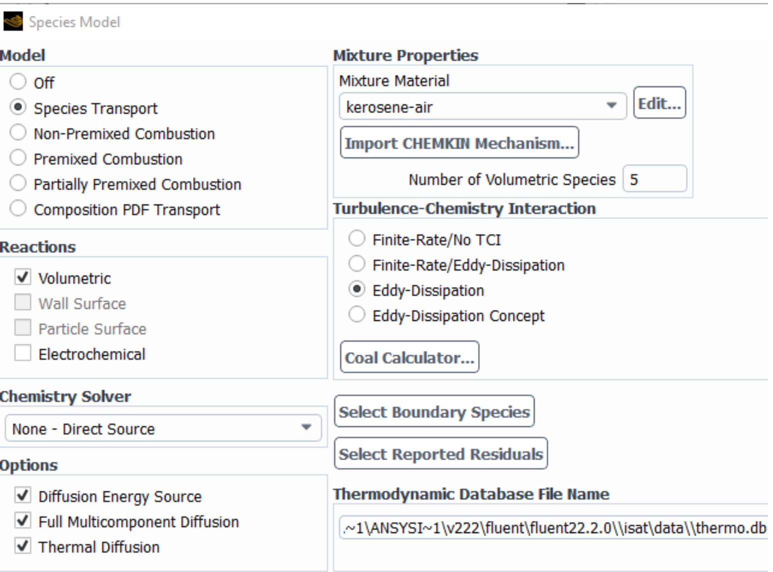
☐ Include Backward Reaction
☐ Third-Body Efficiencies
☐ Pressure-Dependent Reaction
☐ Coverage-Dependent Reaction

Mixing Rate

A: 4
B: 0.5

Reaksiyon Modelleme

- Katılımcılardan bu aşamada beklenen yanma modeli ‘Species Transport’ modelini kullanmalarıdır. Eğer kullanıcılar farklı bir yanma modeli kullanmayı tercih ediyorlarsa sebeplerini açıklamalıdır.
- Art yakıcılarda akış yanma odalarının aksine hızlıdır. Yani akış sıkıştırılabilir rejimdedir. Malzeme özelliklerinden sıkıştırılabilirliği göz önüne olacak bir yoğunluk modeli seçilmelidir.
- Son olarak kullanılan reaksiyon modeli aşağıda gözükmektedir. Tek bir denklemli yanma modeli olup kerosen’in en basit yanmasını içermektedir. Bu aşamada katılımcıların daha fazla sayıda denklem kullanması teşvik edilip bonus puan verilecektir.



Species Model

Model
○ Off
● Species Transport
○ Non-Premixed Combustion
○ Premixed Combustion
○ Partially Premixed Combustion
○ Composition PDF Transport

Reactions
☑ Volumetric
☐ Wall Surface
☐ Particle Surface
☐ Electrochemical

Chemistry Solver
None - Direct Source

Options
☑ Diffusion Energy Source
☑ Full Multicomponent Diffusion
☑ Thermal Diffusion

Mixture Properties
Mixture Material: kerosene-air
Number of Volumetric Species: 5

Turbulence-Chemistry Interaction
○ Finite-Rate/No TCI
○ Finite-Rate/Eddy-Dissipation
● Eddy-Dissipation
○ Eddy-Dissipation Concept

Thermodynamic Database File Name
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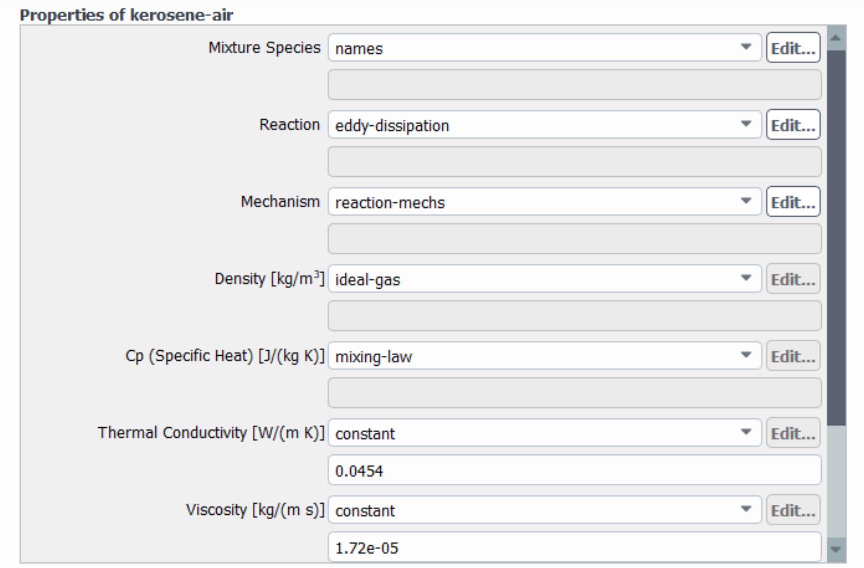
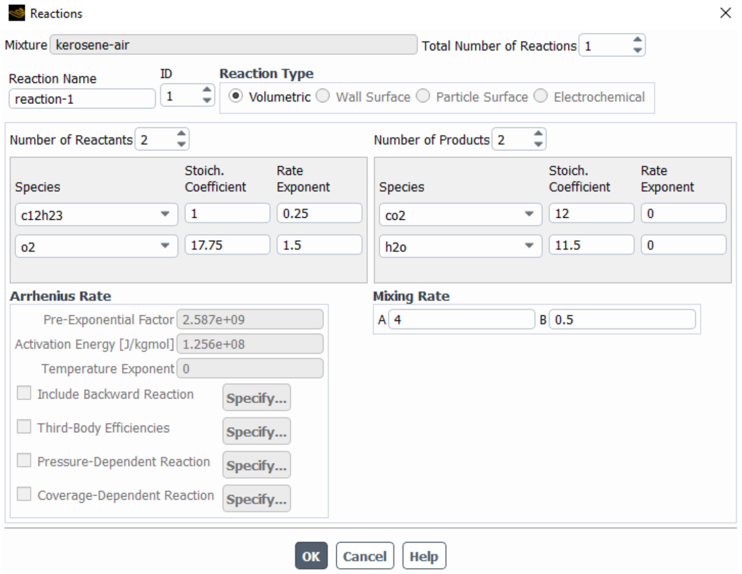


Properties of kerosene-air

Mixture Species	names	Edit...
Reaction	eddy-dissipation	Edit...
Mechanism	reaction-mechs	Edit...
Density [kg/m^3]	ideal-gas	Edit...
Cp (Specific Heat) [J/(kg K)]	mixing-law	Edit...
Thermal Conductivity [W/(m K)]	constant 0.0454	Edit...
Viscosity [kg/(m s)]	constant 1.72e-05	Edit...



Reactions

Mixture: kerosene-air
Total Number of Reactions: 1
Reaction Name: reaction-1
ID: 1
Reaction Type: ● Volumetric ○ Wall Surface ○ Particle Surface ○ Electrochemical

Number of Reactants: 2

Species	Stoich. Coefficient	Rate Exponent
c12h23	1	0.25
o2	17.75	1.5

Number of Products: 2

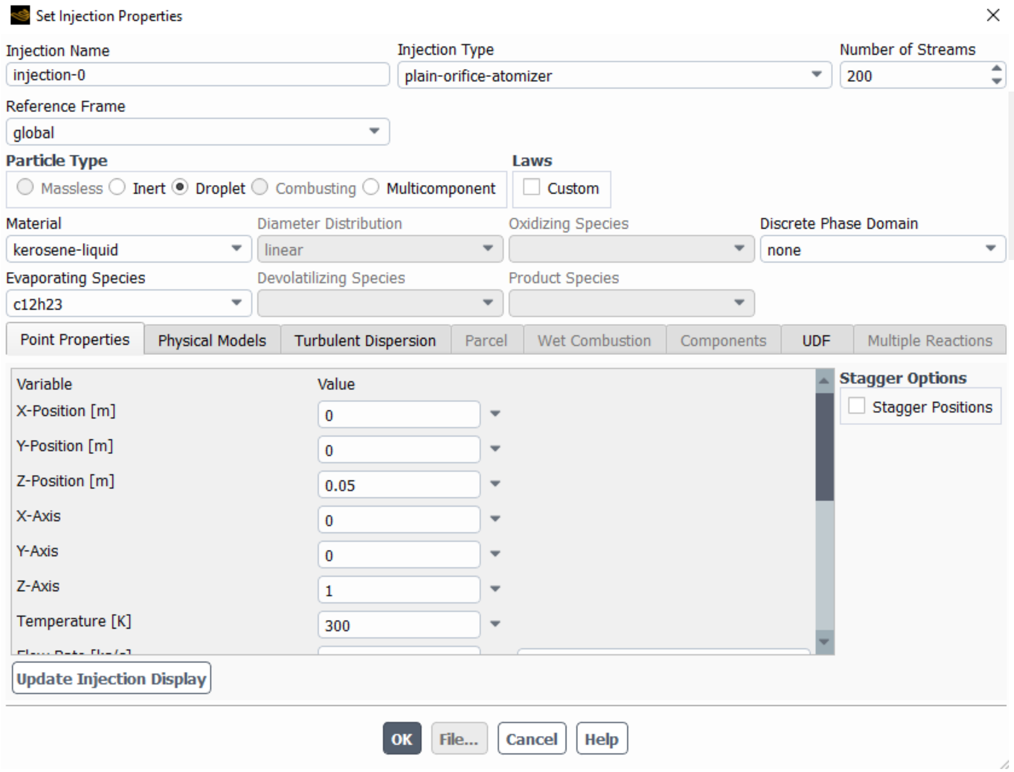
Species	Stoich. Coefficient	Rate Exponent
co2	12	0
h2o	11.5	0

Arrhenius Rate
Pre-Exponential Factor: 2.587e+09
Activation Energy [J/kgmol]: 1.256e+08
Temperature Exponent: 0
☐ Include Backward Reaction
☐ Third-Body Efficiencies
☐ Pressure-Dependent Reaction
☐ Coverage-Dependent Reaction

Mixing Rate
A: 4
B: 0.5

Spray Modelleme

- Örnek bir spray modellemesi gözükmektedir.
- Katılımcıların kullandıkları spray modelini neden seçtiklerini **kısaca** anlatmaları beklenmektedir.
- Katılımcılar kullandıkları modelde literatürdeki enjektör çap ve uzunluk değerlerini araştırarak kendi analizlerine yansıtmaları beklenmektedir.
- Ayrıca break-up sürecinini ne olduğunun da anlatılması beklenmektedir.



Injection Name: injection-0
Injection Type: plain-orifice-atomizer
Number of Streams: 200
Reference Frame: global

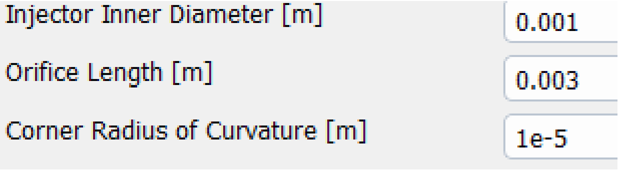
Particle Type: ○ Massless ○ Inert ● Droplet ○ Combusting ○ Multicomponent

Laws: ☐ Custom

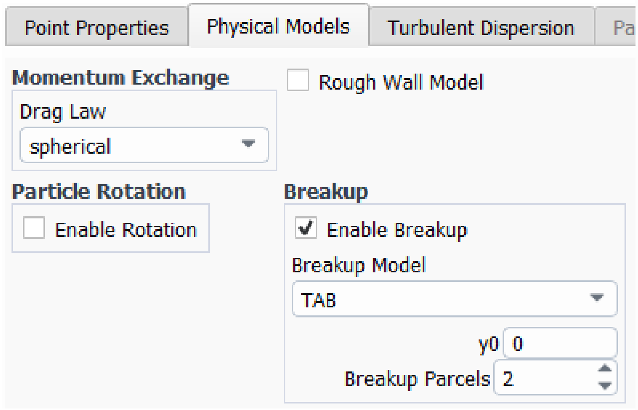
Material: kerosene-liquid
Diameter Distribution: linear
Oxidizing Species:
Discrete Phase Domain: none
Evaporating Species: c12h23
Devolatilizing Species:
Product Species:

Variable	Value
X-Position [m]	0
Y-Position [m]	0
Z-Position [m]	0.05
X-Axis	0
Y-Axis	0
Z-Axis	1
Temperature [K]	300

Stagger Options: ☐ Stagger Positions



Injector Inner Diameter [m]: 0.001
Orifice Length [m]: 0.003
Corner Radius of Curvature [m]: 1e-5

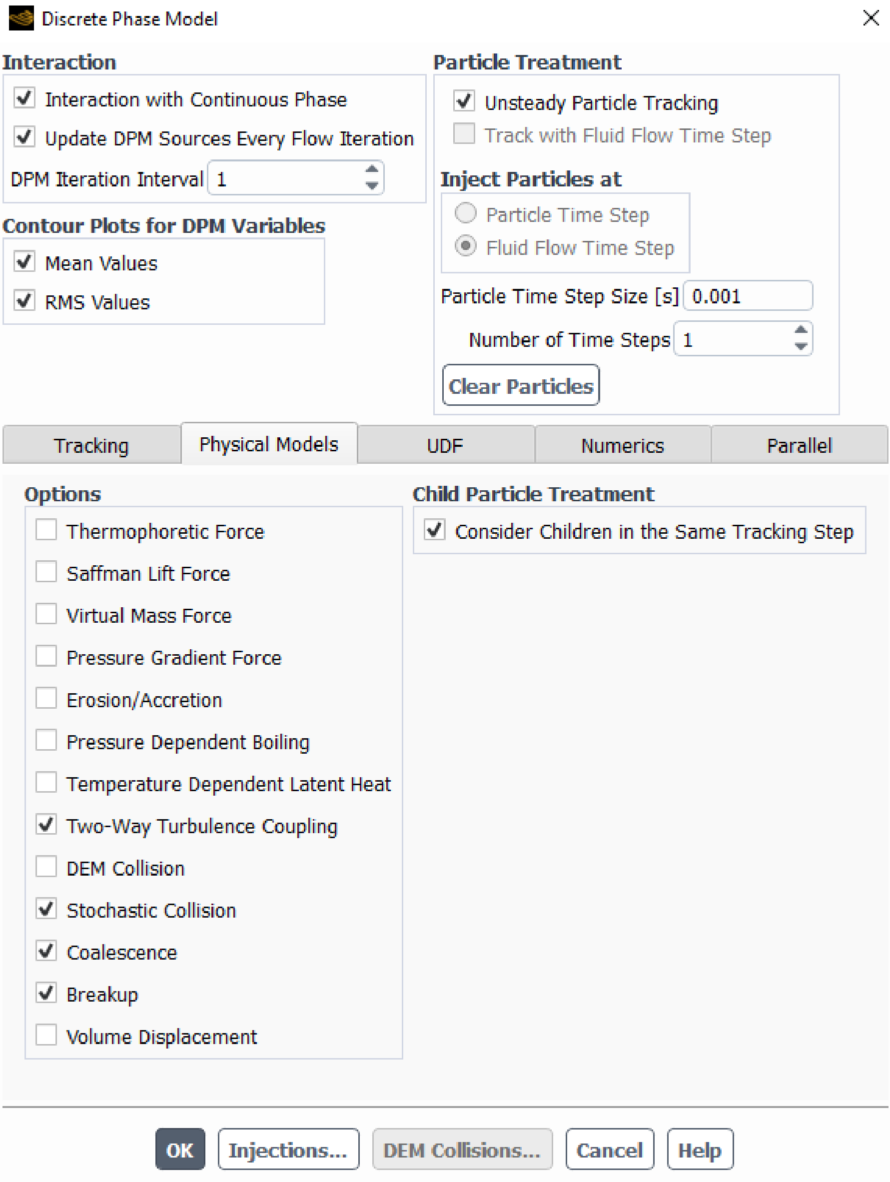


Momentum Exchange
Drag Law: spherical

☐ Rough Wall Model

Particle Rotation
☐ Enable Rotation

Breakup
☑ Enable Breakup
Breakup Model: TAB
y0: 0
Breakup Parcels: 2



Interaction
☑ Interaction with Continuous Phase
☑ Update DPM Sources Every Flow Iteration
DPM Iteration Interval: 1

Contour Plots for DPM Variables
☑ Mean Values
☑ RMS Values

Particle Treatment
☑ Unsteady Particle Tracking
☐ Track with Fluid Flow Time Step

Inject Particles at
○ Particle Time Step
● Fluid Flow Time Step

Particle Time Step Size [s]: 0.001
Number of Time Steps: 1

Options
☐ Thermophoretic Force
☐ Saffman Lift Force
☐ Virtual Mass Force
☐ Pressure Gradient Force
☐ Erosion/Accretion
☐ Pressure Dependent Boiling
☐ Temperature Dependent Latent Heat
☑ Two-Way Turbulence Coupling
☐ DEM Collision
☑ Stochastic Collision
☑ Coalescence
☑ Breakup
☐ Volume Displacement

Child Particle Treatment
☑ Consider Children in the Same Tracking Step

Spray Modelleme

- Bir spray barda sıvının 3 farklı rejimiyle karşılaşılabilmektedir.
- Kullancılardan bu 3 rejimin ne olduğu artıları ve eksilerinin neler olduğunun **kısaca** anlatılması beklenmektedir.
- Bu rejimlerin enjektör tasarım parametreriyle de ilişkilendirilmesi beklenmektedir.

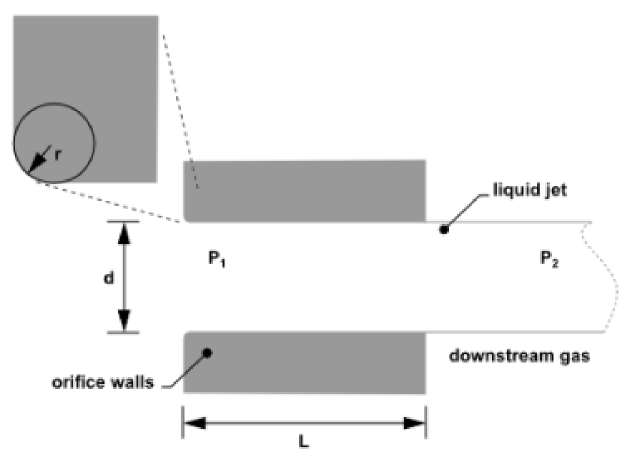


Figure 12.15: Single-Phase Nozzle Flow (Liquid Completely Fills the Orifice)

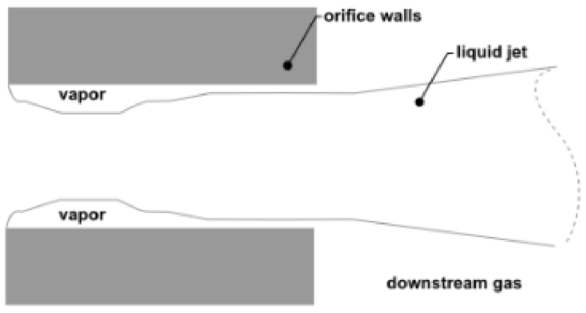


Figure 12.16: Cavitating Nozzle Flow (Vapor Pockets Form Just After the Inlet Corners)

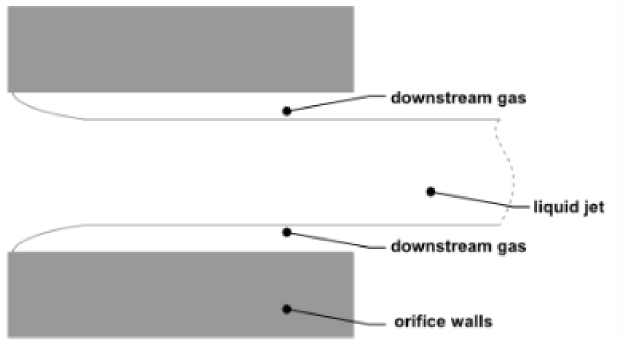
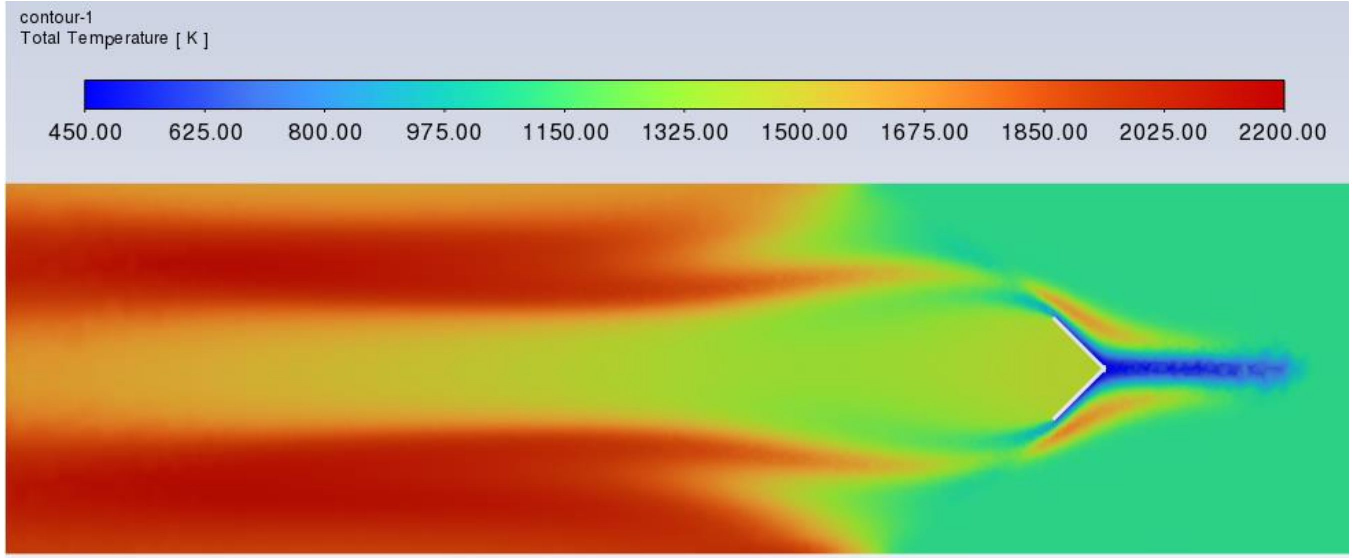
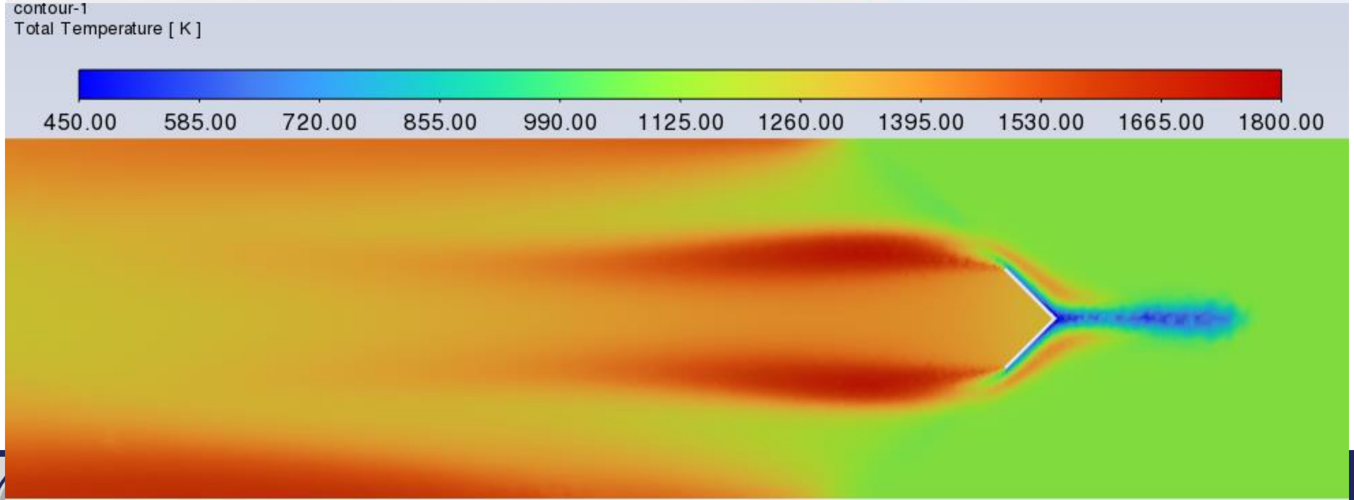


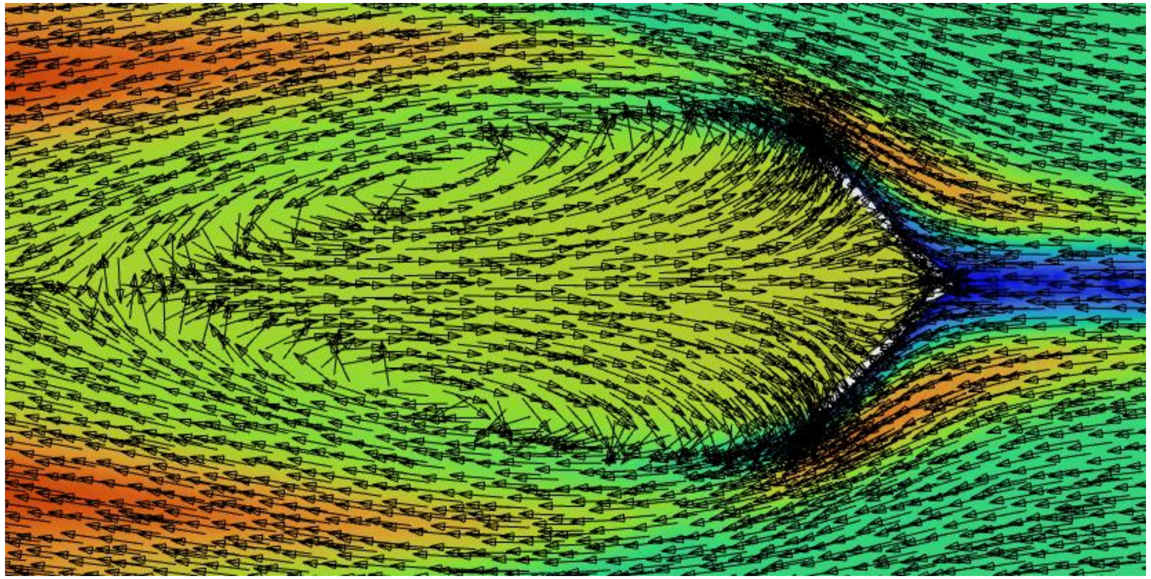
Figure 12.17: Flipped Nozzle Flow (Downstream Gas Surrounds the Liquid Jet Inside the Nozzle)

Örnek Problem

- Bir V-gutter etrafındaki reaktif akış aşağıdaki gibi görülmektedir.
- Bu problemde spray, reaksiyon, türbülans modellenmiş olup karışık bir mühendislik probleminin nümerik olarak nasıl modelleneceğine dair katılımcılara yol gösterecektir.







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WHAT IS COMBUSTION?

Combustion is the one of the most important topic of classical physics that is combination of fluid mechanics, heat and mass transfer, chemistry and turbulence. Today, it is not still fully-understood subject. However, the simplest definition for the combustion is the exothermic chemical reaction that occurs by mixing of fuel and oxidizer in moleculer level.

In engineering applications, the combustion is not enough alone. The combustion process must be controlled in a chamber and gained energy from this process. This chamber can be a gas turbine burner, industrial furnace, cylinder of a piston engine, burner of a heating boiler etc.

Combustor design is an art, not a science.

J. N. Murthy

GOVERNING EQUATIONS OF REACTING FLOWS

- Consider a problem which contains flow and heat transfer

- Continuity

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = S_M$$

- Momentum

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + S_F$$

- Energy

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho h u_j)}{\partial x_j} = \frac{Dp}{Dt} - \frac{\partial q_j}{\partial x_j} + \tau_{ij}\frac{\partial u_i}{\partial x_j} + Q + S_H + S_E$$

- For a reacting flow, conservation equations of chemical species must be solved

$$\frac{\partial (\rho Y_k)}{\partial t} + \frac{\partial (\rho Y_k u_j)}{\partial x_j} = -\frac{\partial J_{k,j}}{\partial x_j} + \dot{\omega}_k + S_Y \qquad k = 1,2,3,\dots N$$

$* \, Y_k \; is\ the\ mass\ fraction\ of\ specie\ k$

$$C_{12}H_{23} + 17.75(O_2 + 3.76N_2) \xrightarrow{reaction} 12CO_2 + 11.5H_2O + 66.74N_2$$

- For a 3D reacting flow problem

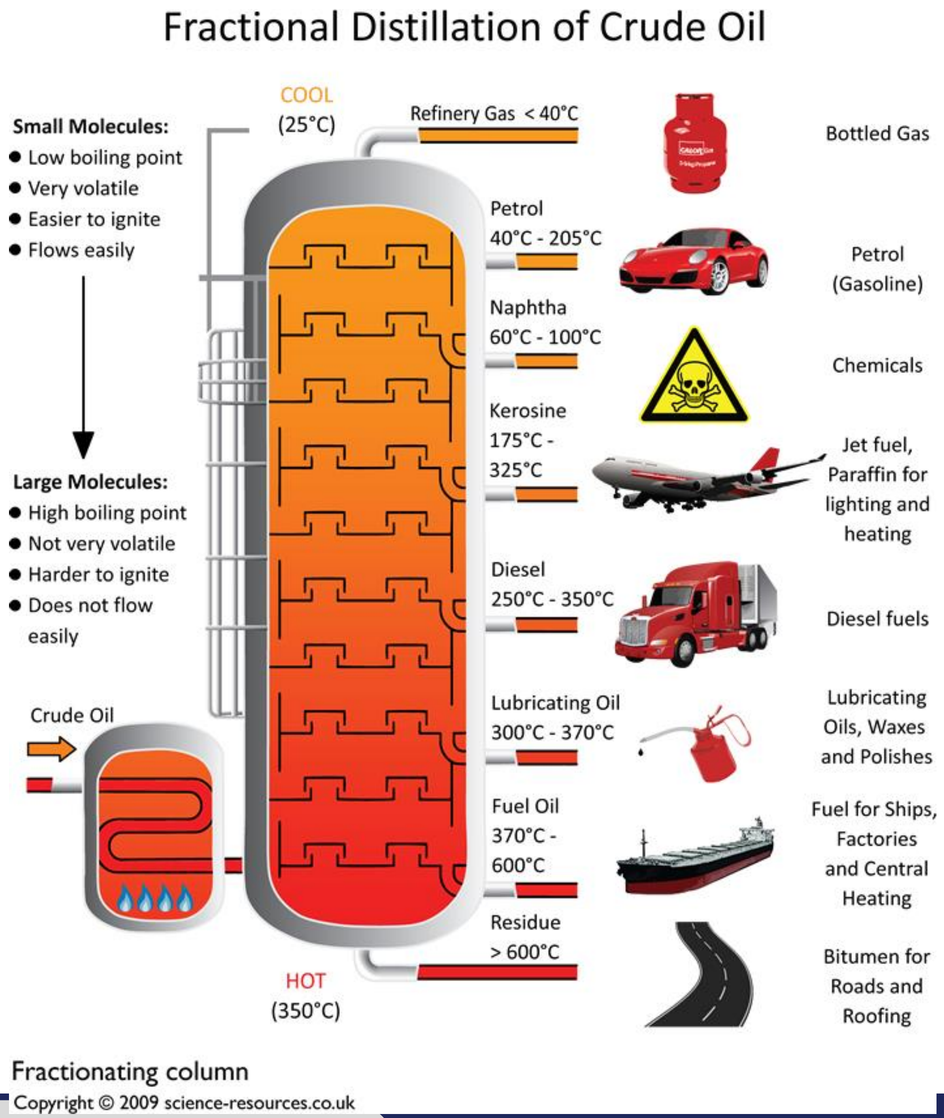
  5 equations + N-1 equations

- For a 3D turbulent reacting flow problem

  + X equations more according to selected turbulence approach

JET FUELS

https://en.wikipedia.org/wiki/Jet_fuel



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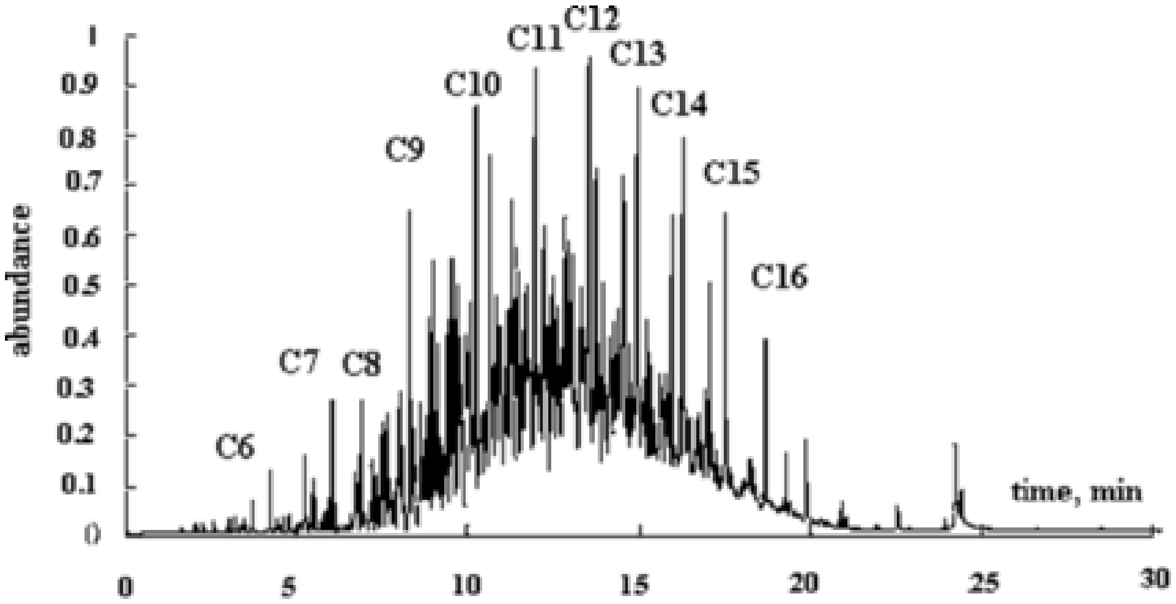


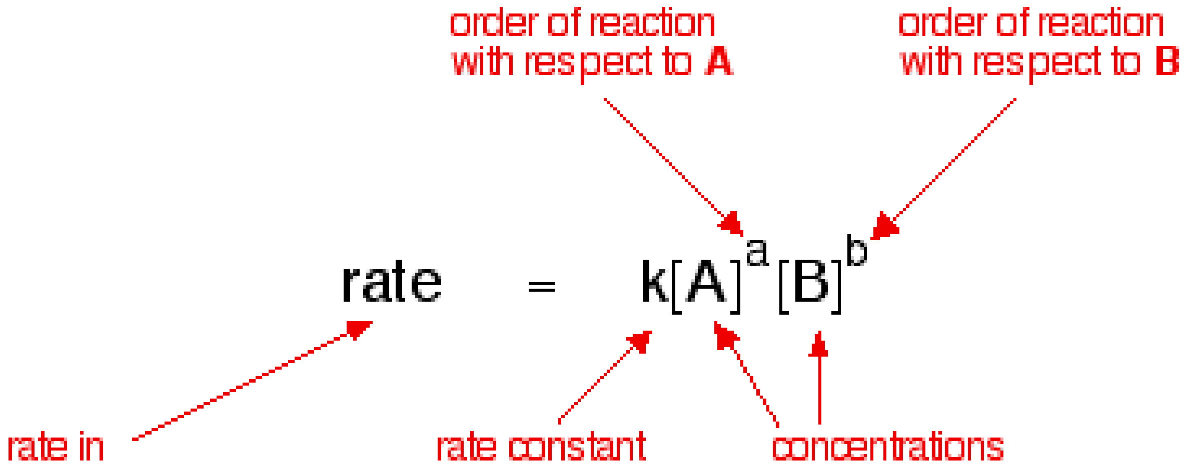
Kerosene Kromatogram

- Kerosene fuel consists of hundreds of species and thousands of reaction steps.
- In many application, detailed chemical mechanisms are not practical and hence, simplified fuel models are used.

$$C_{12}H_{23} + 17.75(O_2 + 3.76N_2) \xrightarrow{reaction} 12CO_2 + 11.5H_2O + 66.74N_2$$

CHEMICAL REACTIONS

For example, suppose you had a reaction between two substances A and B. Assume that at least one of them is in a form where it is sensible to measure its concentration - for example, in solution or as a gas.



order of reaction with respect to **A**

order of reaction with respect to **B**

$$\text{rate} = k[A]^a[B]^b$$

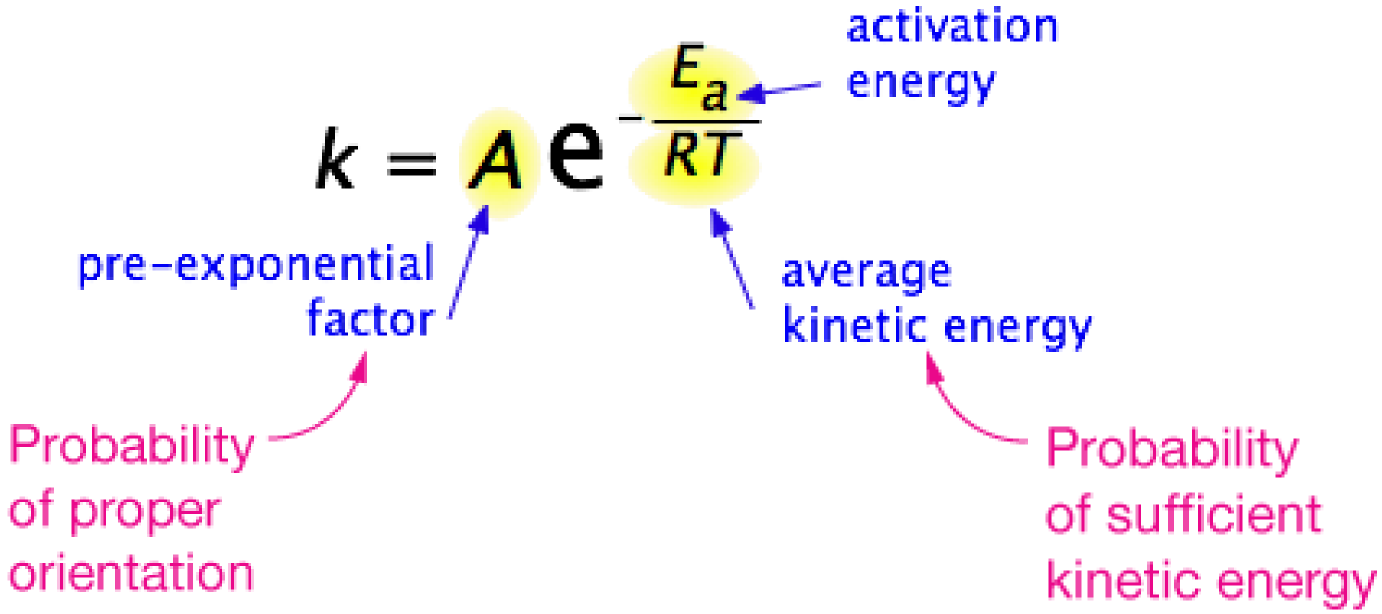
rate in

rate constant

concentrations

CHEMICAL REACTIONS

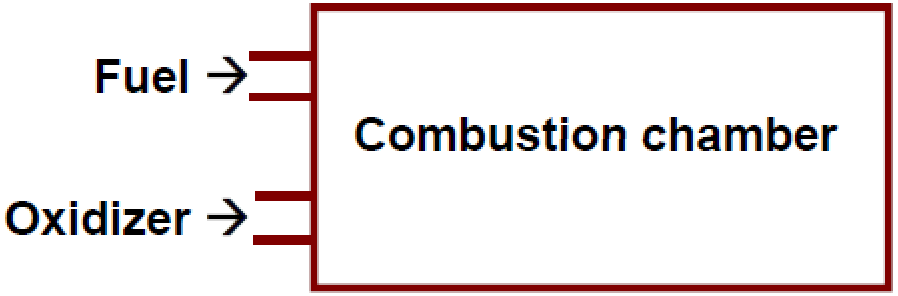
The Arrhenius equation:



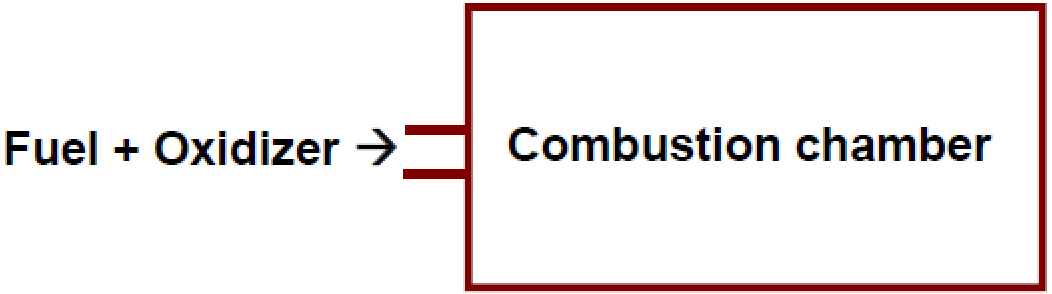
Where;

- T is temperature in K
- R is gas constant
- E_a is the minimum energy needed for the reaction to occur
- A is a term which includes factors like the frequency of collisions and their orientation.

FLAMES vs FLOW CONFIGURATION



Ön Karışımsız (Non-Premixed/Diffusion)



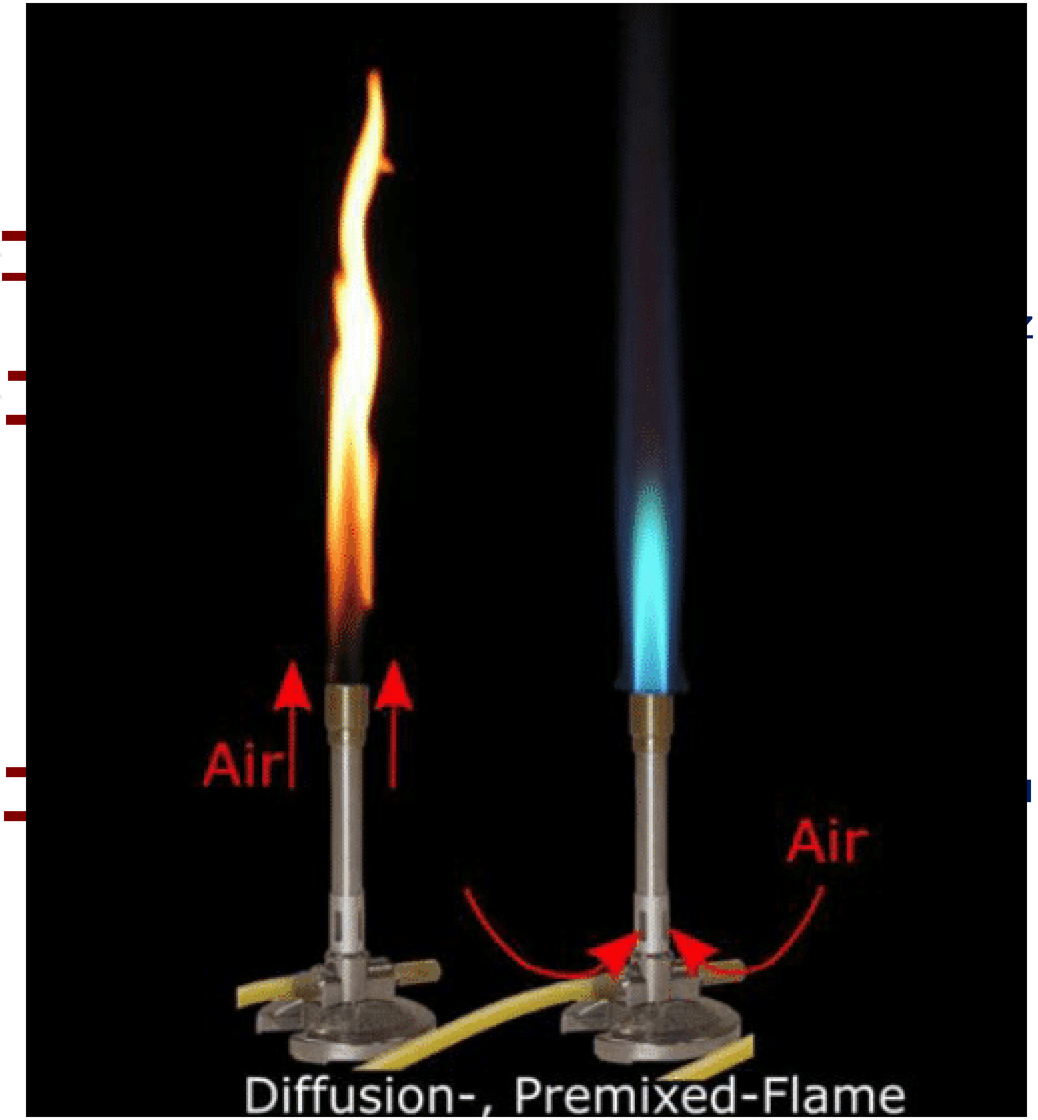
Ön Karışımlı (Premixed)

FLAMES vs FLOW CONFIGURATION

Fuel →

Oxidizer →

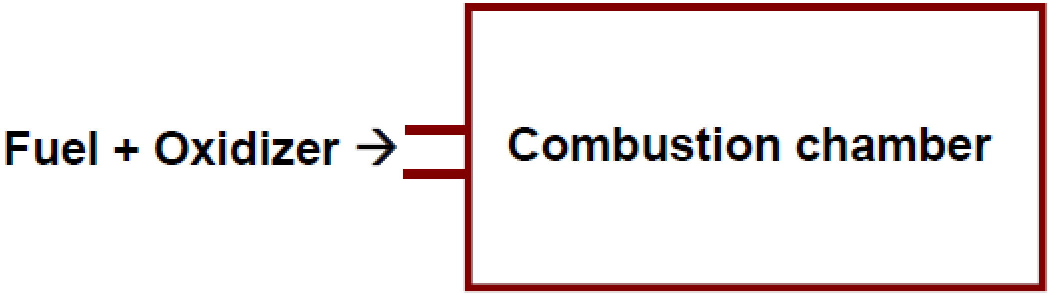
Fuel + Oxidizer →

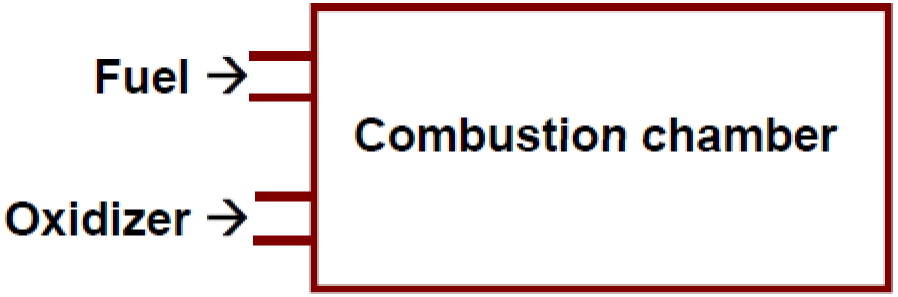


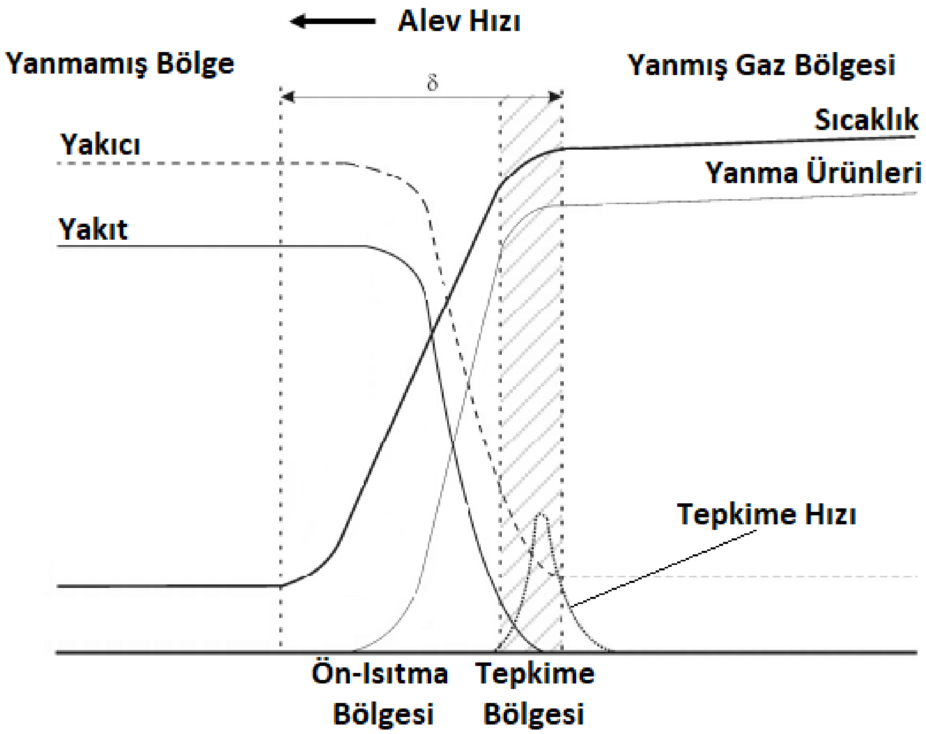
(Non-Premixed/Diffusion)

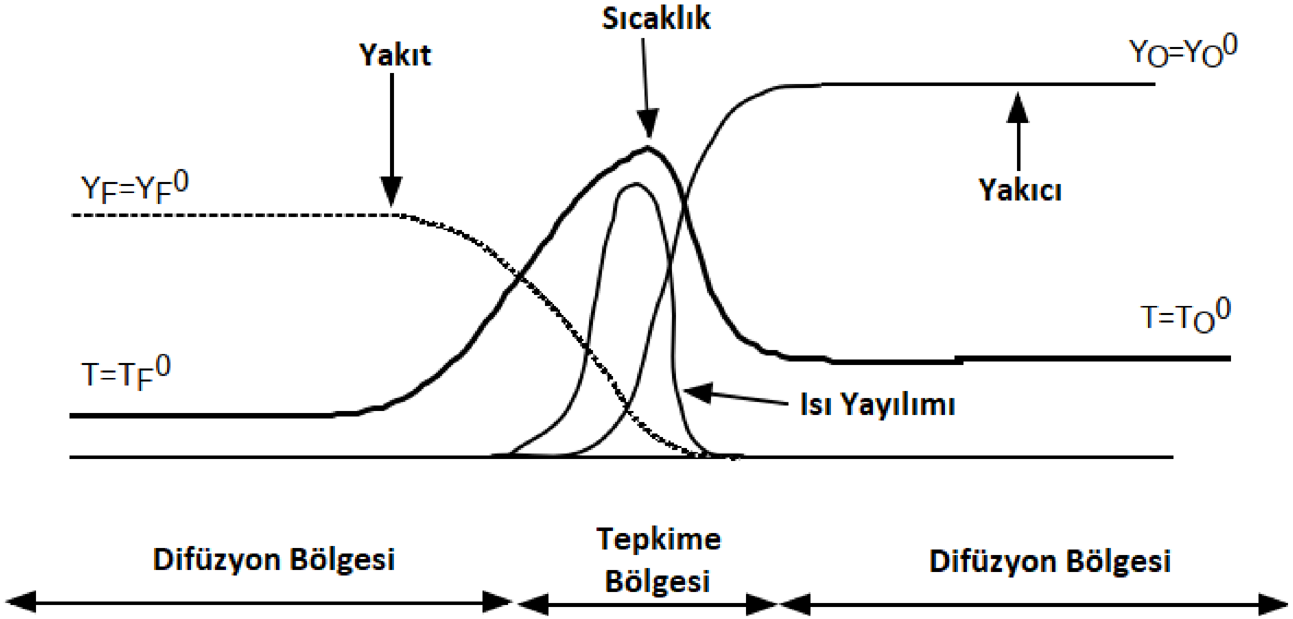
(Premixed)

FLAMES vs FLOW CONFIGURATION



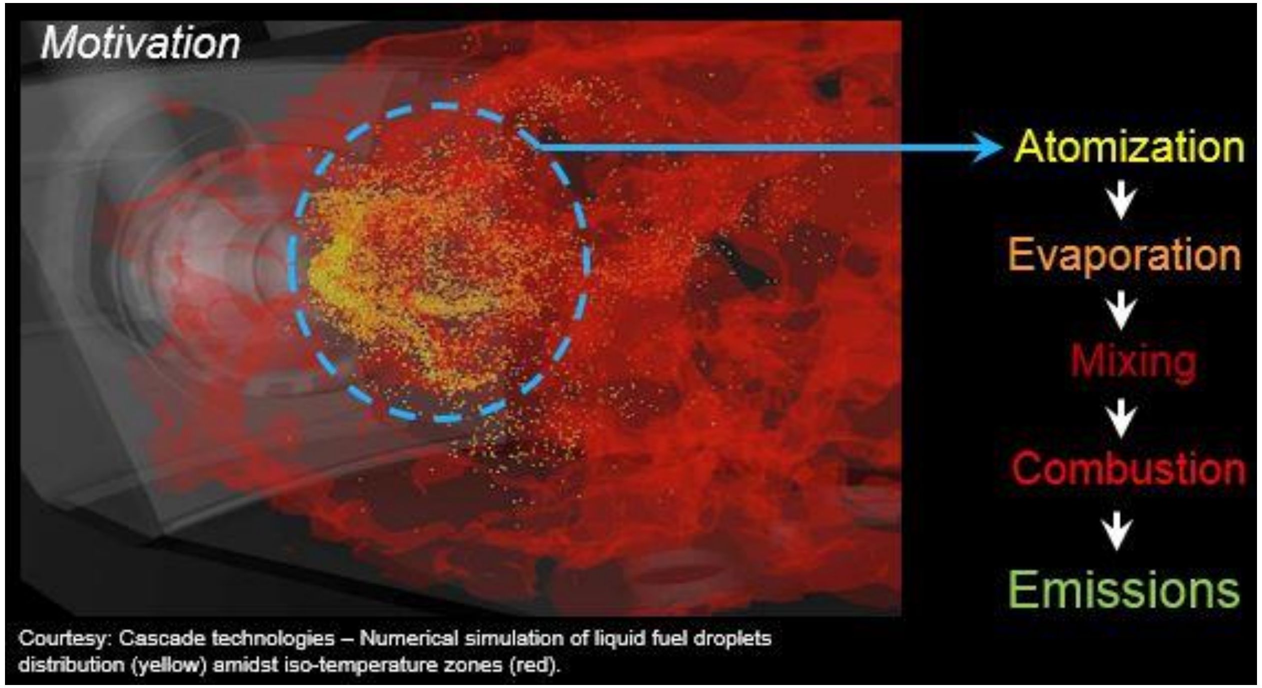




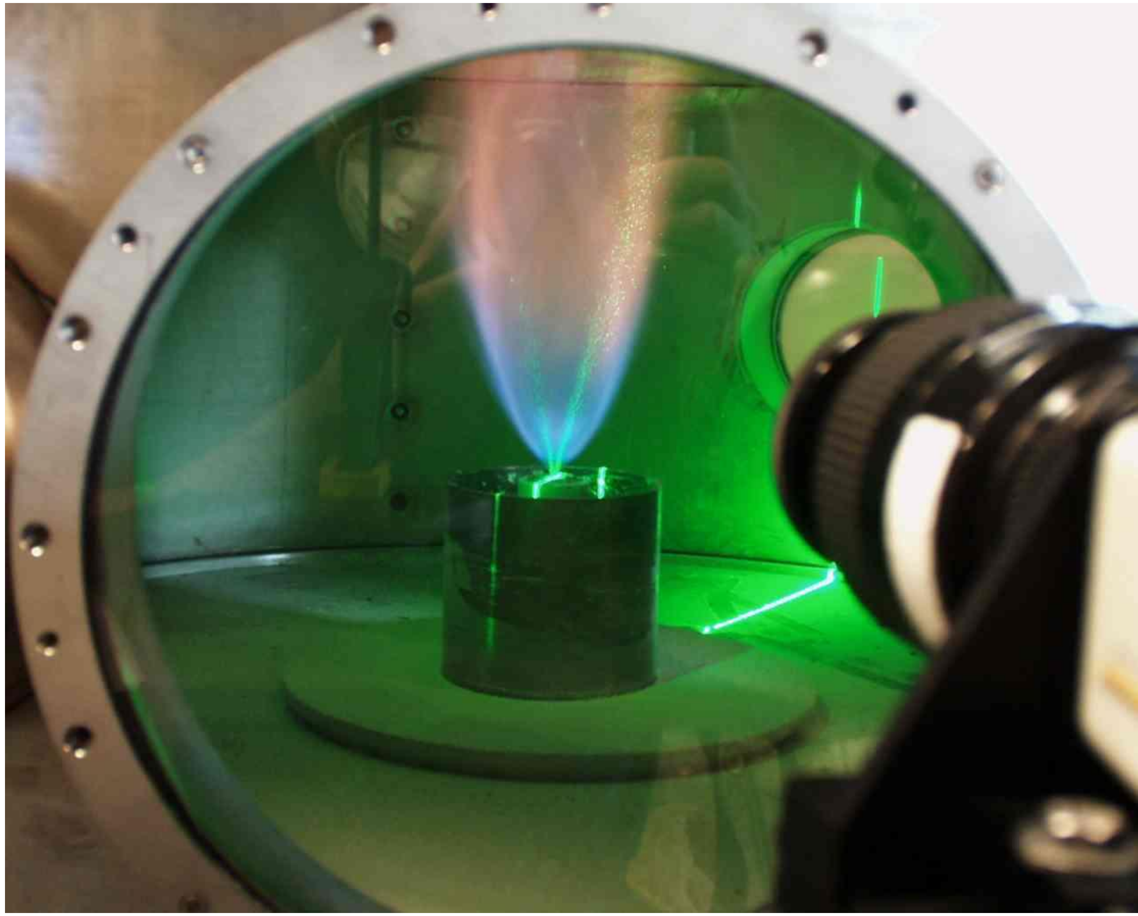


FLAMES vs FLOW CONFIGURATION

Intentionally or unintentionally, many combustion systems have partially premixed systems.

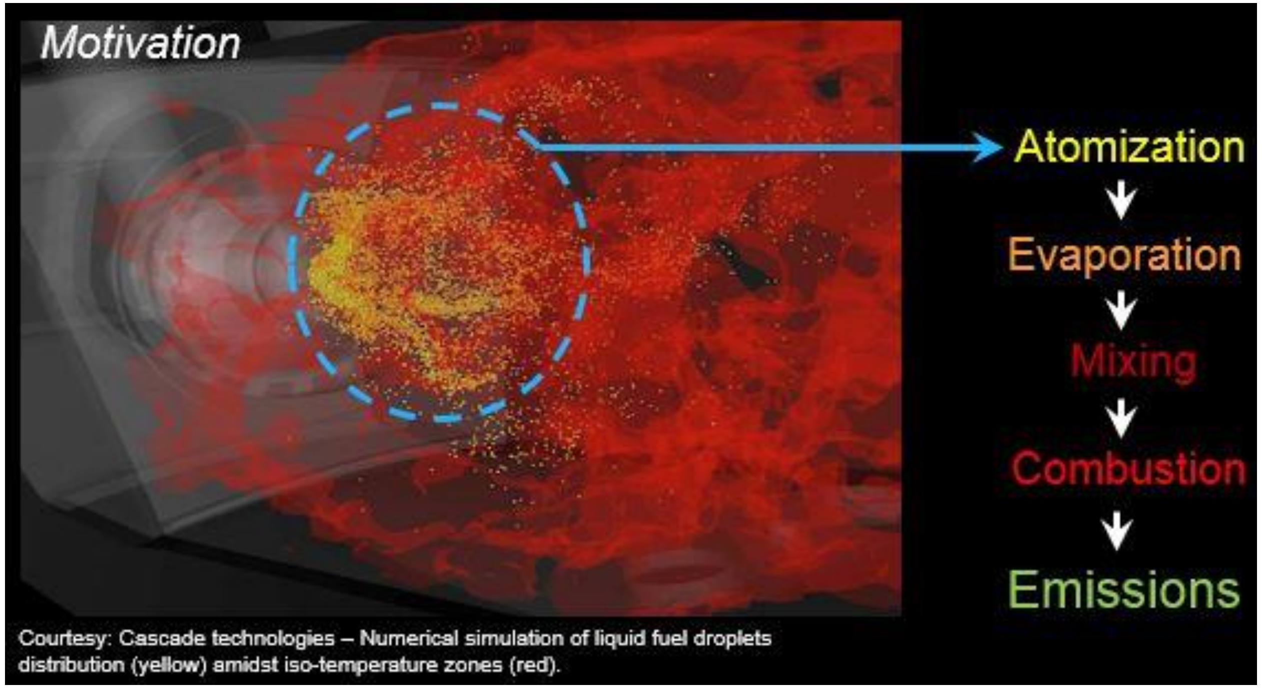


Courtesy: Cascade technologies – Numerical simulation of liquid fuel droplets distribution (yellow) amidst iso-temperature zones (red).

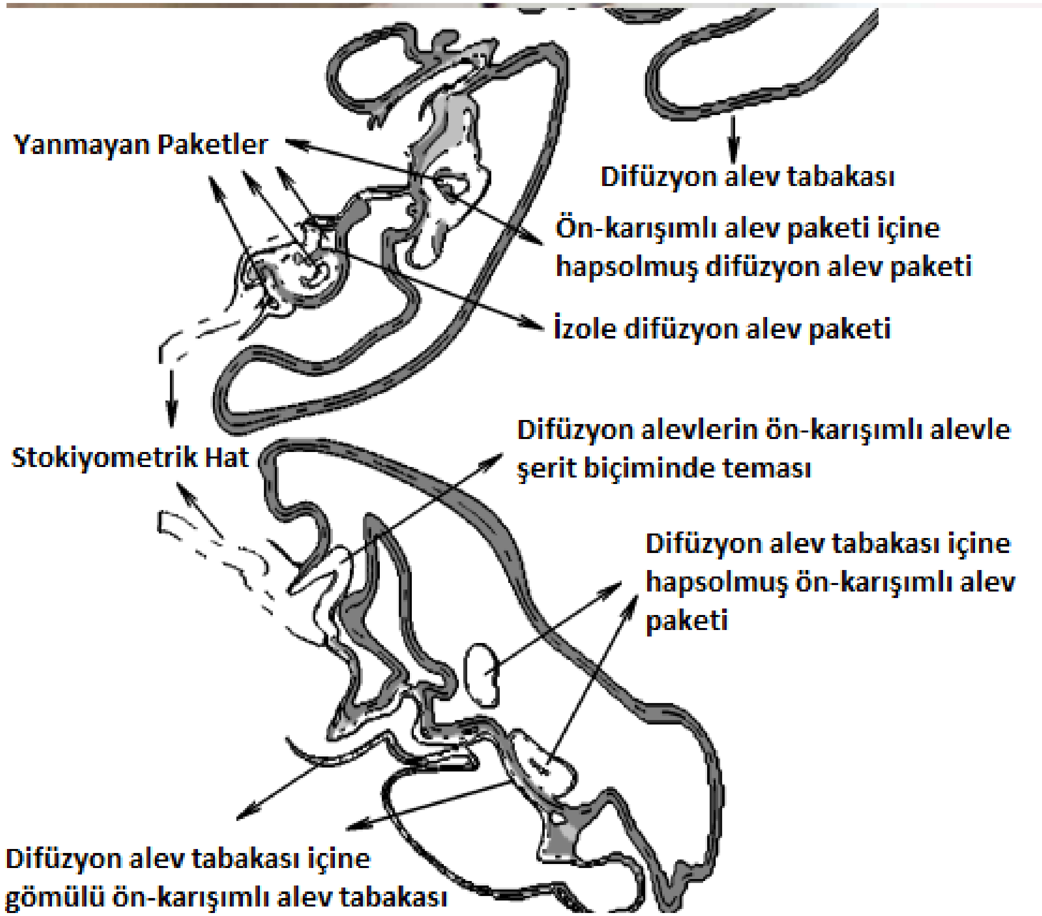


FLAMES vs FLOW CONFIGURATION

Intentionally or unintentionally, many combustion systems have partially premixed systems.



Courtesy: Cascade technologies – Numerical simulation of liquid fuel droplets distribution (yellow) amidst iso-temperature zones (red).



CHEMISTRY APPROACH

Although combustion is a chemical process it may not always be the reaction rate that determines how fast a fuel burns. The ratio of the mixing timescale to a combustion timescale, known as the Damköhler number, determines the controlling physics.

$$Da = \frac{t_M}{t_R} = \frac{mixing\ time}{reaction\ time}$$

- For large Damköhler numbers ($Da \gg 1$) , it is the mixing of the reactants in a diffusion flame or transport of products in premixed combustion that determine the rate of consumption of the fuel. (Infinitely Fast Chemistry)

- In all other situations the chemical reaction rate plays a role and finite rate chemistry models are needed. (Finite Rate Chemistry)

COMBUSTION MODELS

- In the literature and CFD solvers, many combustion models are available.
- It is important to choose a proper combustion model that can capable to solve desired physics and also is not computationally expensive.
  - Some models are valid for only premixed and non-premixed combustion however, some models cover all combustion regimes.
    - In Example: C-Equation for premixed combustion, Steady Laminar Flamelets Model for non-premixed combustion and Eddy Dissipation Model for all regimes.

  - Infinitely Fast Chemistry vs Finite Rate Chemistry?
    - Depends on Da Number
    - Pollutants such as CO, Nox etc. are products of slow chemistry

  - Global or Detailed Chemistry
    - For design iterations, tailored global mechanisms (1-5 step reactions) are suitable for determining the flame position.
    - For ignition, quenching and emissions, detailed chemistry should be used.

TUSAŞ MOTOR SANAYİİ A.Ş.
TUSAŞ ENGINE INDUSTRIES, INC.

GÜCÜN KAYNAĞI

TEŞEKKÜRLER

TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Termal Sistem Tasarım Teknik Eğitim

10.01.2023

CONTENT

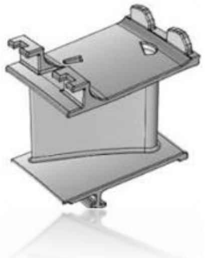
- Introduction to Heat Transfer in Gas Turbines
- Heat Transfer Interfaces
- Heat Transfer Mechanisms in Gas Turbines
    - Conduction
    - Convection
    - Radiation
- 1D - Resistance Network Approach
- SAS & Component Cooling Concepts
- Afterburner Examples
- Effusion Cooling
- Film Cooling
- Closing Remarks

TEKNOFEST
HAVACILIK, UZAY VE TEKNOLOJİ FESTİVALİ

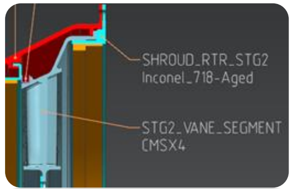
Heat Transfer in Gas Turbines: Thermal Analysis Step

INPUTS

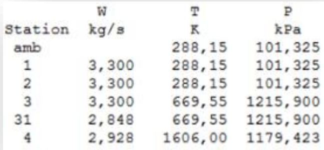
Mechanical Design
- **Geometry**



Material
- **Thermophysical Properties**

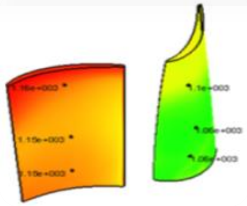


Performance
- **Cycle Information**



Station	W kg/s	T K	P kPa
amb		288,15	101,325
1	3,300	288,15	101,325
2	3,300	288,15	101,325
3	3,300	669,55	1215,900
31	2,848	669,55	1215,900
4	2,928	1606,00	1179,423

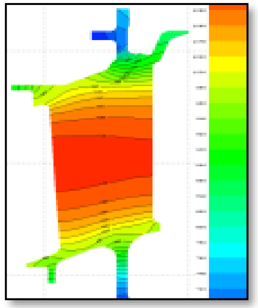
Aerodynamic / Combustion Design
- **Gas Temps**
- **HTC**

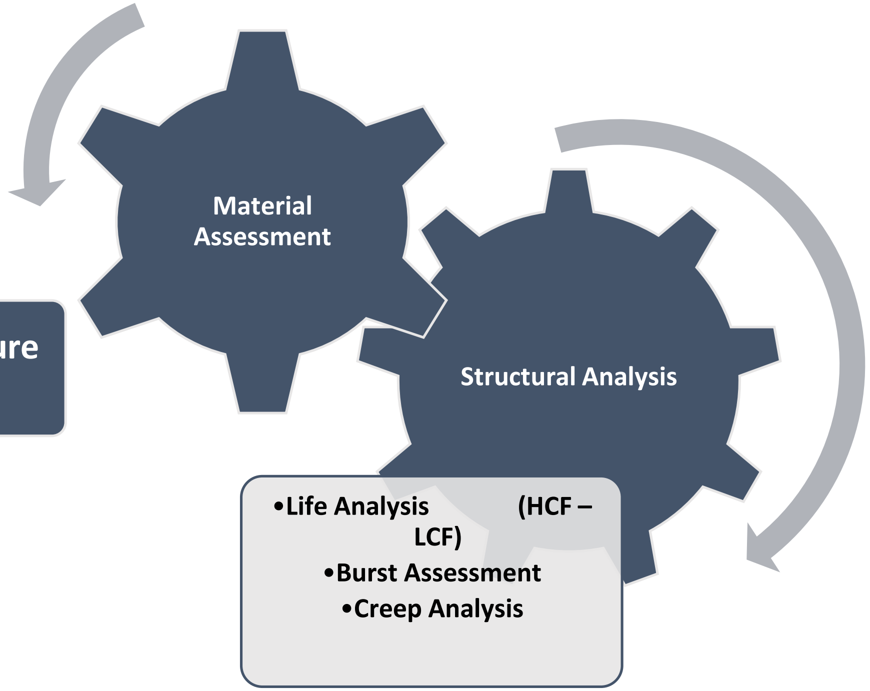


Secondary Air Systems
- **Cooling Mechanism**
- **HTC**

Thermal Analysis
Thermal System Design

Metal Temperature Distribution





Material Assessment

Structural Analysis

- **Life Analysis (HCF – LCF)**
- **Burst Assessment**
- **Creep Analysis**

Thermal analysis should be carried out by using *Geometry, Material, Performance, Aero* and *SAS* boundary condition. *Material* and *Structural* assessments should be done in accordance with the metal temperature distribution.

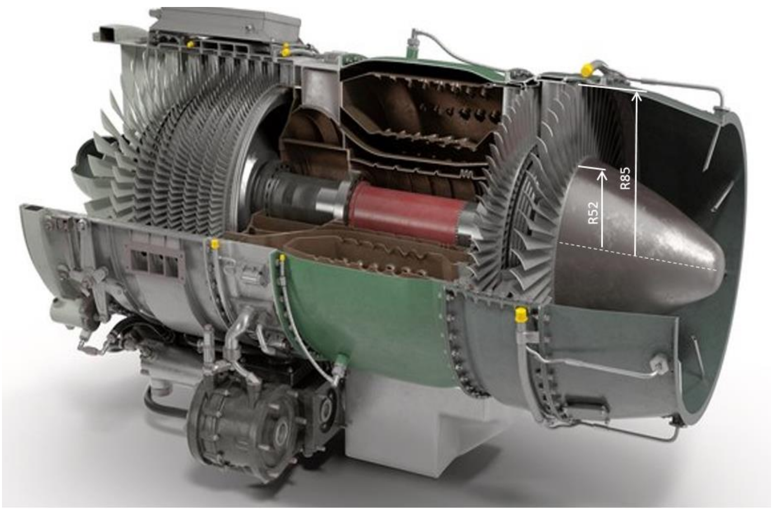
Teknofest Afterburner Design

Inputs:

- Absolute Total Pressure= 300 kPa
- Absolute Total Temperature= 1050 K
- Mass Flow Rate (Primary Zone)= 3.6 kg/s
- Coolant Temperature= 540 K
- Coolant Pressure=720 kPa
- Mass Flow Rate (Secondary Zone)= 0.8 kg/s

Requirements:

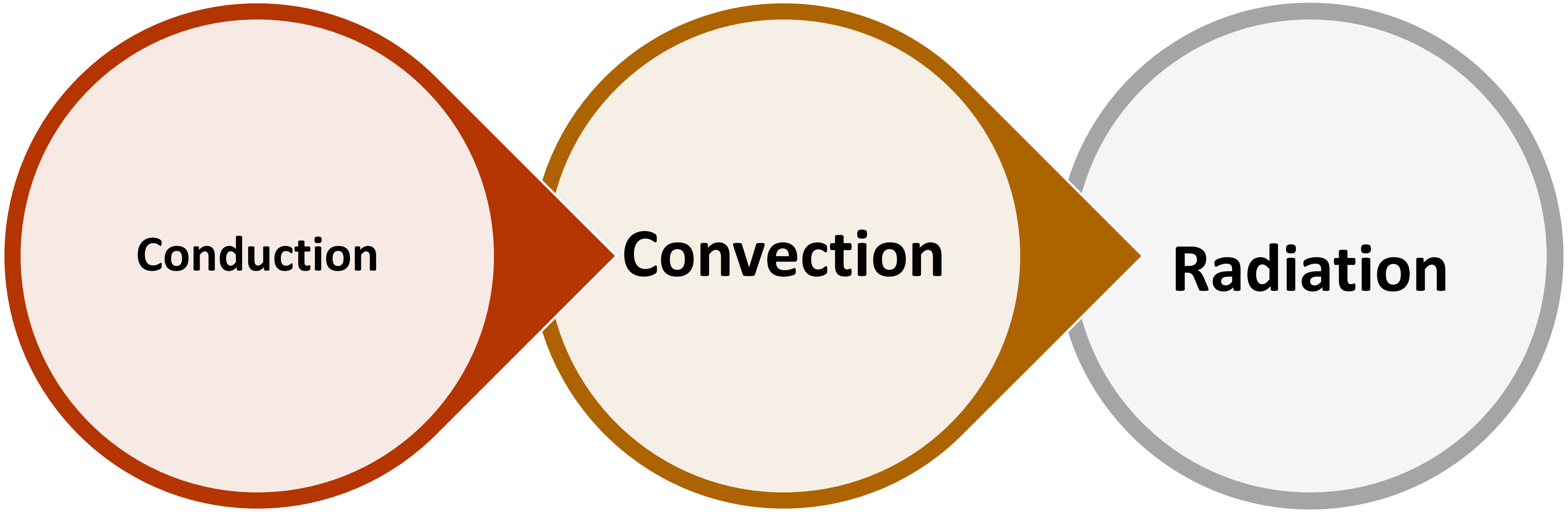
- Maximum allowable metal temperature= 1270 K
- Required life= 25 h



DDR:

- **Thermal Analysis (1D/2D)**
  - *Implementation of Boundary Condition*
  - *Flame Temperature & Radiation*
  - *Cooling Configuration Choosing & Design*
  - *Heat Transfer Circuit*
- **Material and Mechanical Relations**

Heat Transfer Mechanisms



- Floating Contacts
- Pressure Faces
- Interference Fits
- Disk, casing and airfoils

- Flowpath – Airfoil
- Secondary Air Flows
- Cooling Effects

- Cavities (Rotor – Stator)
- Blade Shank

Heat transfer mechanisms of gas turbines can be listed as conduction, convection and radiation. Domains where relevant heat transfer mechanism are dominant are shown.

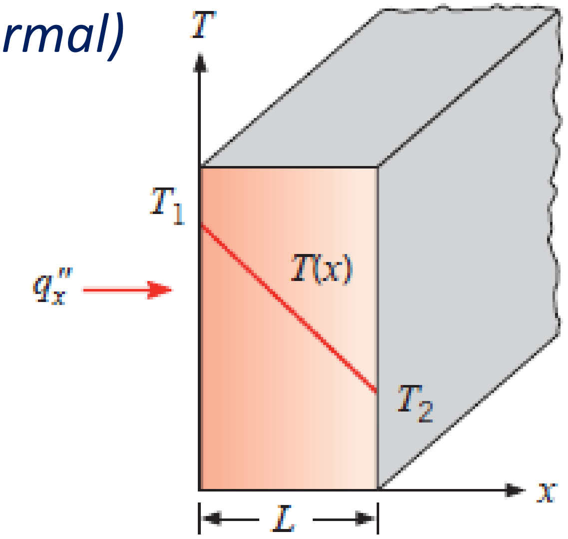
Heat Transfer Mechanisms: Conduction

Conduction

- **Interference Fit**
- **Floating Contacts**
- **Pressure Faces**
- **Disk, casing and airfoils**

- **Heat transfer with conduction:**
  - Thermophysical properties of material is crucial (k, cp)
  - Fouriers law is used for calculation.
- **General heat conduction equations solved by:**
  - *Analytical solution (separation of variables)*
  - *Graphical methods Numerical methods*
  - *Finite element tools (ANSYS, SCO3, P/Thermal)*

$$q_x'' = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L} = -k\frac{dT}{dx}$$



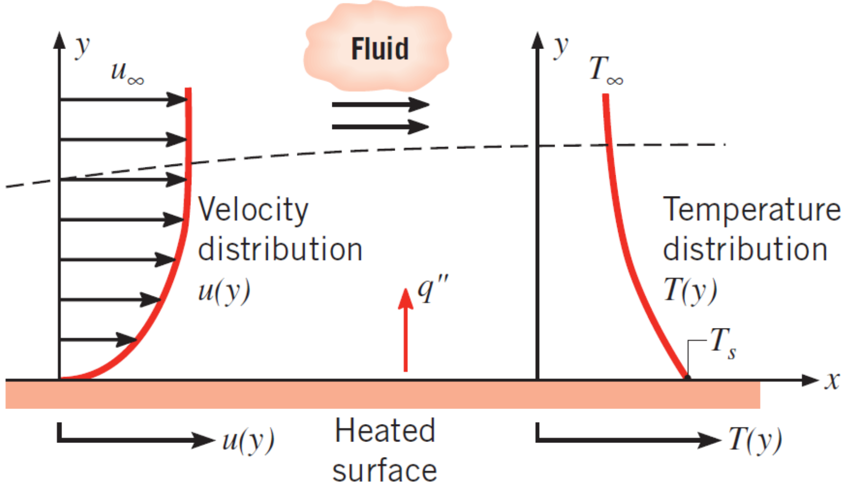
Heat Transfer Mechanisms: Convection

Convection

- **Flowpath – Airfoil**
- **Secondary Air Flows**
- **Cooling Effects**

- **Heat transfer from surface is classifies as;**
  - **Forced Convection:** Fluid motion caused by external agency
  - **Natural Convection:** Fluid motion resulting from density differences due to temperature variations in fluid.
- **Convective heat transfer can be solved by;**
  - *Analytical calculations*
  - *Experimental techniques*
  - *CFD analysis*

$$q'' = h(T_s - T_\infty)$$



Heat Transfer Mechanisms: Dimensionless Numbers

- **Heat transfer coefficients:**
  - Analytical calculations based on empirical equations
  - Empirical equations obtained by correlating experimental data with aid of dimensional analysis.
- **Non-dimensional numbers:**

Nusselt Number:

Forced Convection $$Nu = \frac{hL}{k} = f(Re, Pr)$$

Natural Convection $$Nu = \frac{hL}{k} = f(Gr, Pr)$$

Reynolds Number:

$$Re = \frac{\rho V L}{\mu}$$

Prandtl Number:

$$Pr = \frac{c_p \mu}{k}$$

Grashof Number:

$$Gr = \frac{\beta g L^3 \Delta T}{v^2}$$

Heat Transfer Mechanisms

- **Adiabatic Wall Temperature**
  - For an adiabatic wall, surface temperature reached under the equilibrium of viscous dissipation and heat conduction in the boundary layer is called Adiabatic Wall Temperature (Taw)
  - Direction of heat transfer to or from the wall depends upon whether the surface temperature is below or above Taw.

$$T_{aw} = T_\infty + \frac{rV_{rel}^2}{2c_p}$$

T_∞ = Free stream fluid temperature
V_{rel} = Free stream fluid velocity relative to the wall

$$Q = HTC*A*(T_{aw}-T_{wall})$$

Turbulent flow: $\mathrm{r} = (Pr)^{1/3}$
Laminar flow: $\mathrm{r} = (Pr)^{1/2}$

Heat Transfer Mechanisms: Radiation

- **Radiative heat transfer is crucial for**
  - Large faces of cavities
  - Domains where temperature difference between corresponding faces

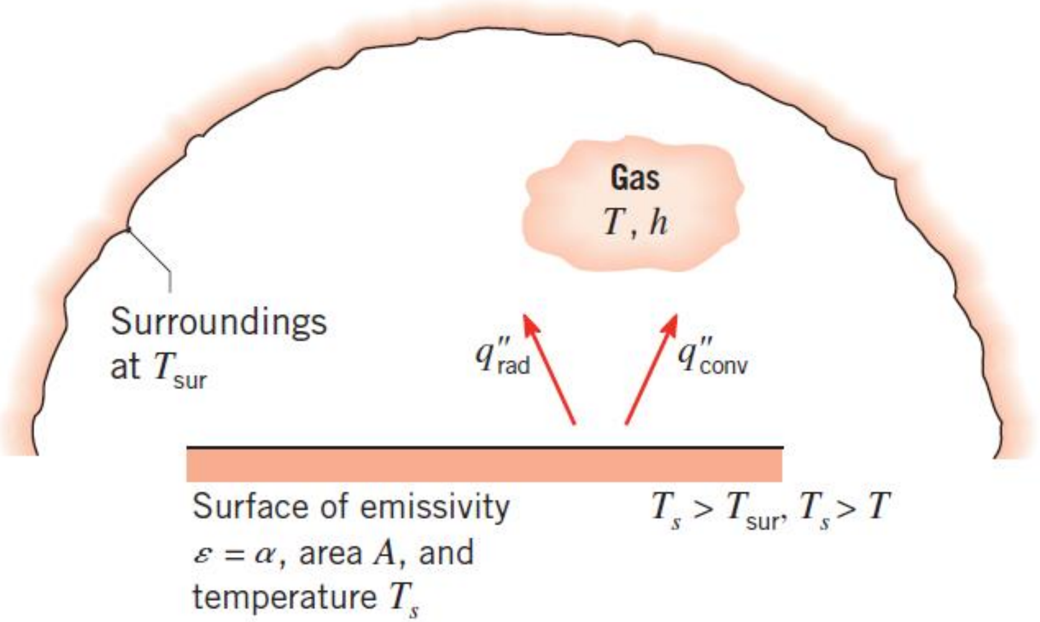
Radiation

- **Cavities (Rotor – Stator)**
- **Blade Shank**

$$q''_{rad} = \mathcal{E}\sigma(T_s^4 - T_{sur}^4)$$

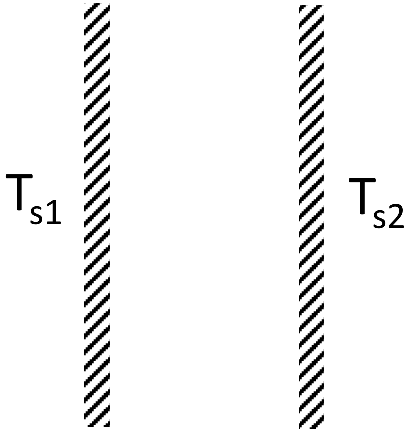
$$\boxed{\begin{array}{c} Stefan - Boltzman\ const: \\ \sigma = 5.67 \times 10^{-8}\ W/m^2K^4 \end{array}}$$

$\mathcal{E}$=Surface emissivity, 0≤ $\mathcal{E}$≤1



Heat Transfer Mechanisms: Radiation

$$\dot{Q}_{1-2} = \frac{\sigma\left(T_{S_1}^4 - T_{S_2}^4\right)}{\left[\left(1-\varepsilon_1\right)/\varepsilon_1 A_1\right] + \left(1/A_1 F_{1-2}\right) + \left[\left(1-\varepsilon_2\right)/\varepsilon_2 A_2\right]}$$



Radiation exchange across gap

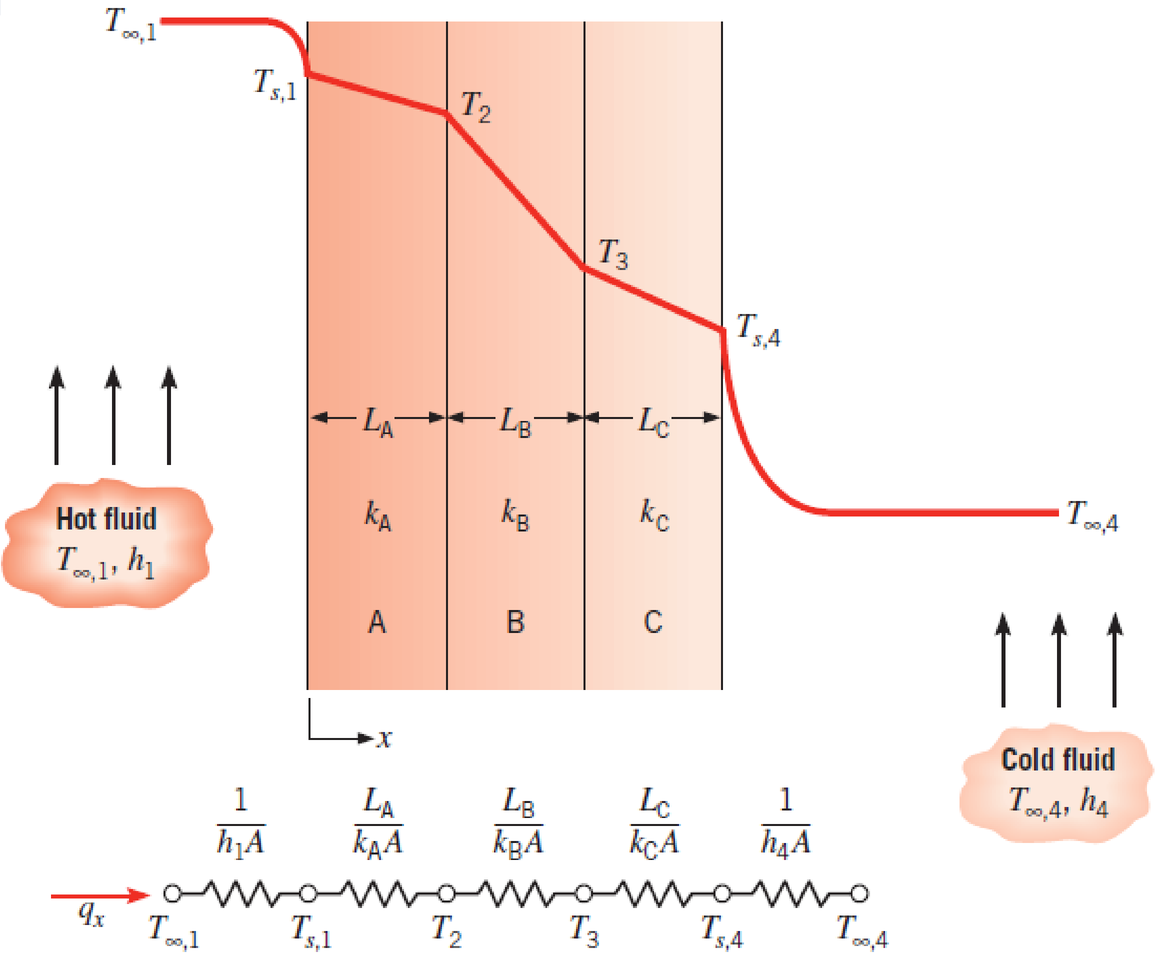
$\dot{Q}_{1-2} \equiv$ Net radiation heat transfer rate from surface 1 to surface 2
$\varepsilon_1 \equiv$ Surface 1 emissivity
$\varepsilon_2 \equiv$ Surface 2 emissivity
$A_1 \equiv$ Heat transfer area of surface 1
$A_2 \equiv$ Heat transfer area of surface 2
$F_{1-2} \equiv$ View factor between surfaces 1 and 2
$T_{S_1} \equiv$ Surface 1 temperature
$T_{S_2} \equiv$ Surface 2 temperature

1D Resistance Network Approach

- 1-D heat transfer analyses play an important role in most conceptual and preliminary designs.
- Resistance network approach can be used for 1D calculations.

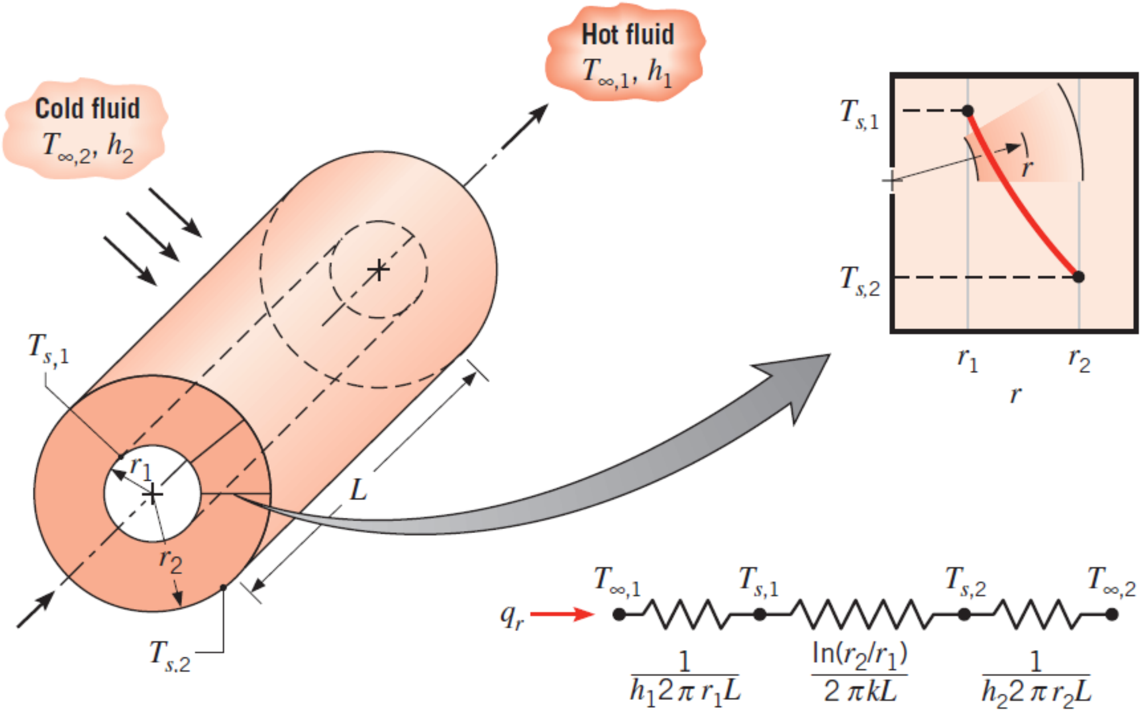
$$\boxed{q_x = UA\Delta T}$$

$$q_x = \frac{T_{\infty,1} - T_{\infty,4}}{[(1/h_1A) + (L_A/k_AA) + (L_B/k_BA) + (L_C/k_CA) + (1/h_4A)]}$$



1D Resistance Network Approach: Radial Systems

- 1-D heat transfer analyses play an important role in most conceptual and preliminary designs.
- Resistance network approach can be used for 1D radial calculations.



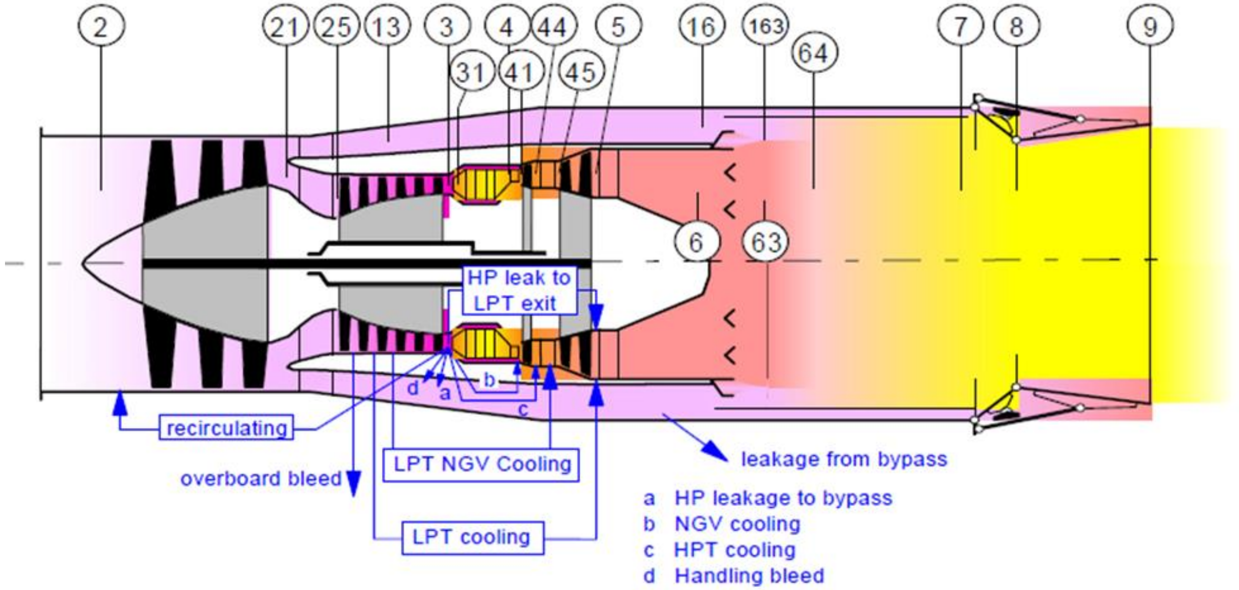
$$\boxed{q_r = \mathrm{UA}(T_{\infty,1} - T_{\infty,4})}$$

$$q_r = \frac{T_{\infty,1} - T_{\infty,4}}{\frac{1}{2\pi r_1 L h_1} + \frac{\ln(r_2/r_1)}{2\pi k_A L} + \frac{\ln(r_3/r_2)}{2\pi k_B L} + \frac{\ln(r_4/r_3)}{2\pi k_C L} + \frac{1}{2\pi r_4 L h_4}}$$

Secondary Air Sytems

SAS Functions on Gas Turbine

- **Cooling Air Supply System**
  - *Turbine Blade –NGV -Shroud*
  - *Linked parts of airfoils*
  - *Case- Sump - **Liner***
- Prevention of Hot Gas Ingestion
- Sealing
- Axial Load Management
- Sump Pressurization
- Anti-Ice System
- Customer / Platform Bleed Air

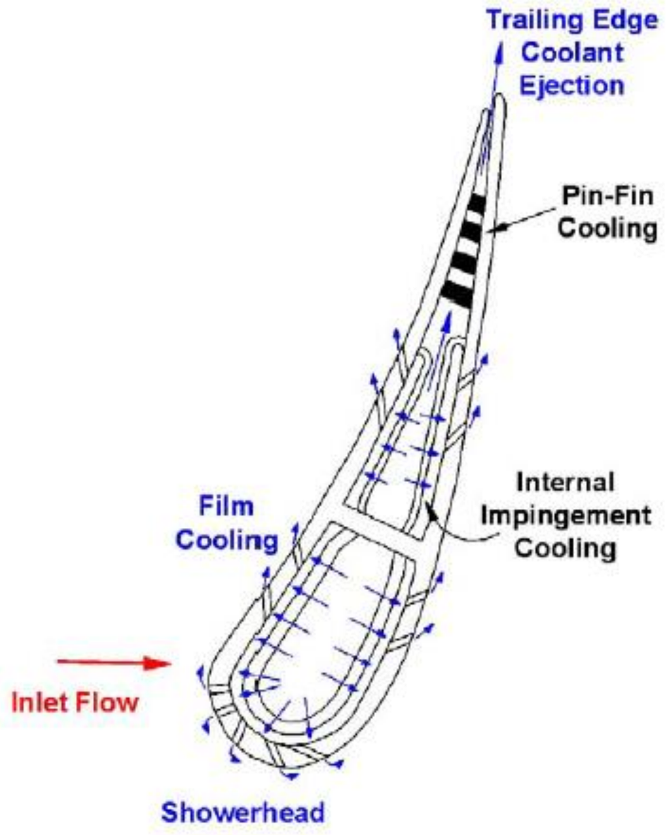


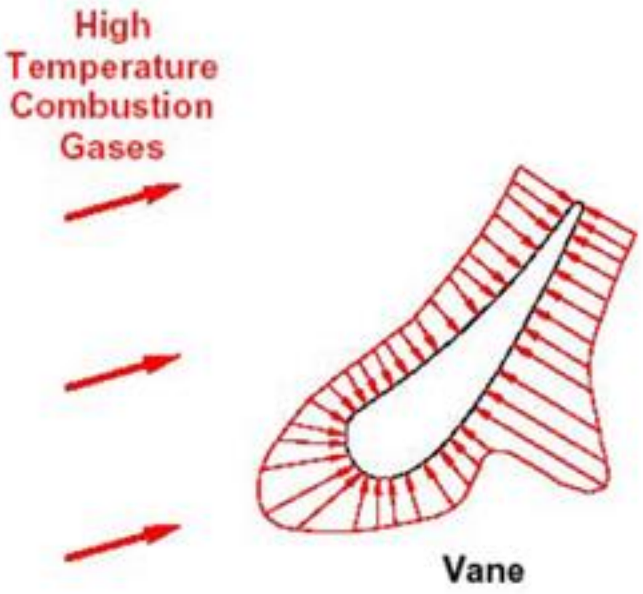
St-0	**Ambient**
St-1	**AirCraft Engine Interface - Engine Inlet**
St-2	**LP Compressor Inlet**
St-13	**ByPass Air**
St-21	**LP Compressor Exit**
St-25	**HP Compressor Inlet**
St-3	**Compressor Exit**

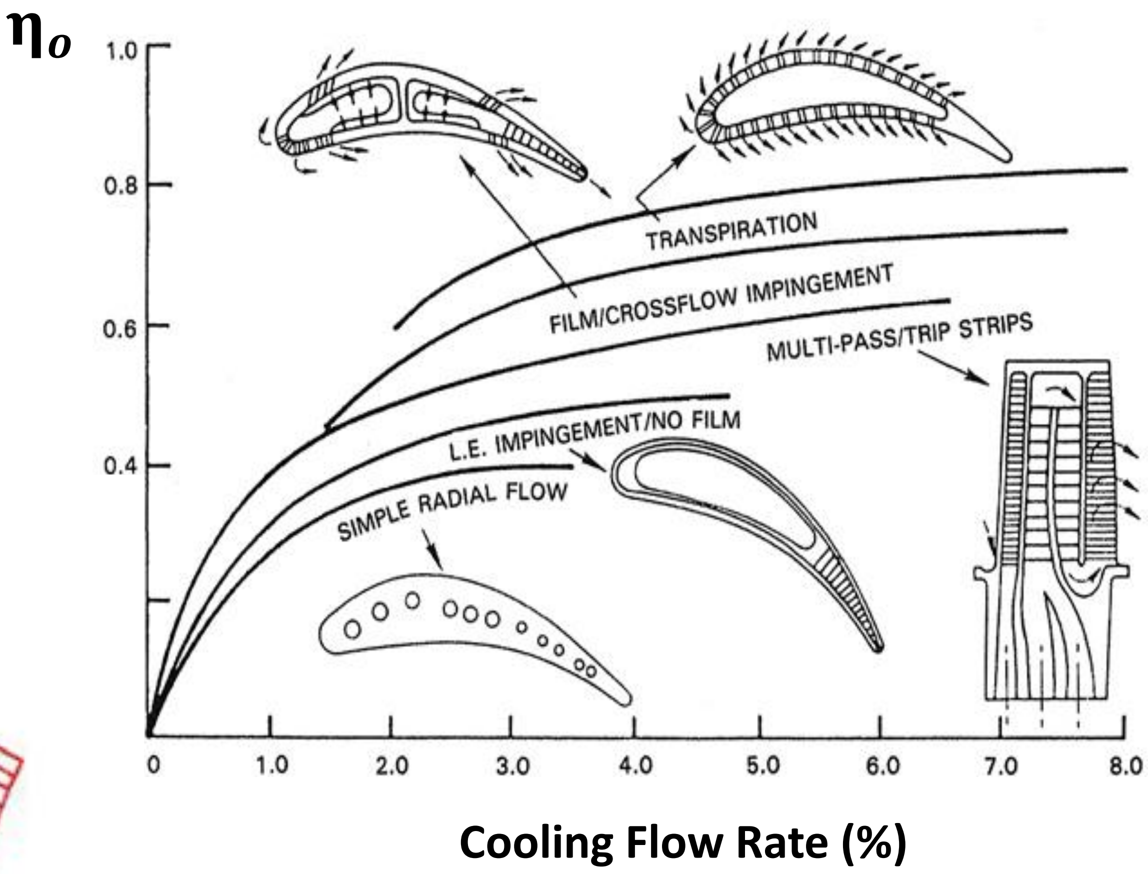
St-4	**Combuster Exit**
St-41	**HP Turbine 1st Stg Rotor Inlet (SOT – Stator Outlet Temperature)**
St-45	**HP Turbine Exit**
St-5	**LP Turbine Exit**
St-6	**After Burner Inlet**
St-7	**Exhaust Inlet**
St-8	**Throat**
St-9	**Exhaust Exit**

$$\dot{m} = \frac{A\hat{F}_{f_t} P_t}{\sqrt{RT_t}} = \frac{AF_{f_t} P_t}{\sqrt{T_t}}$$

Component Cooling Concept

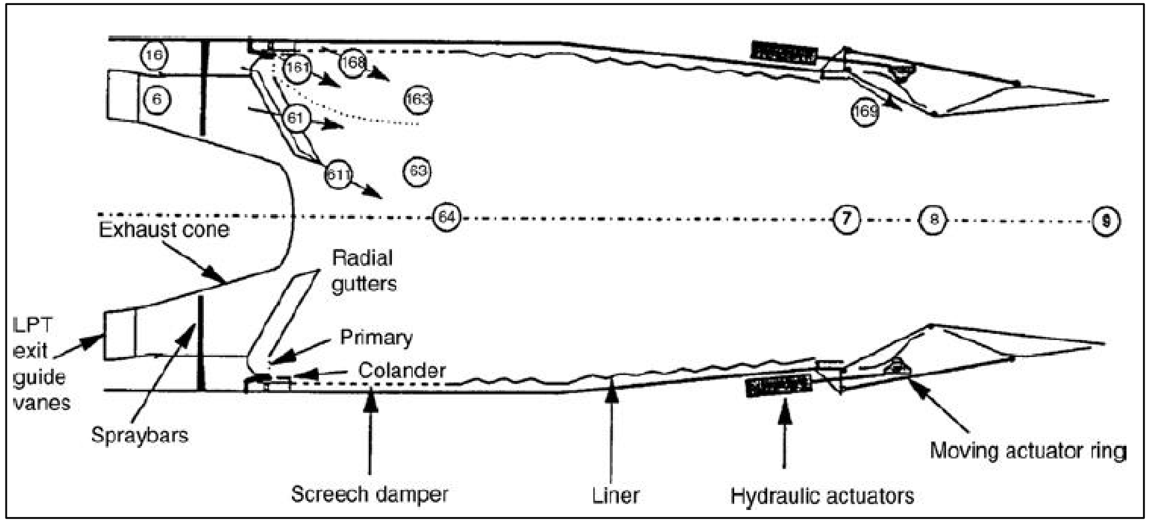




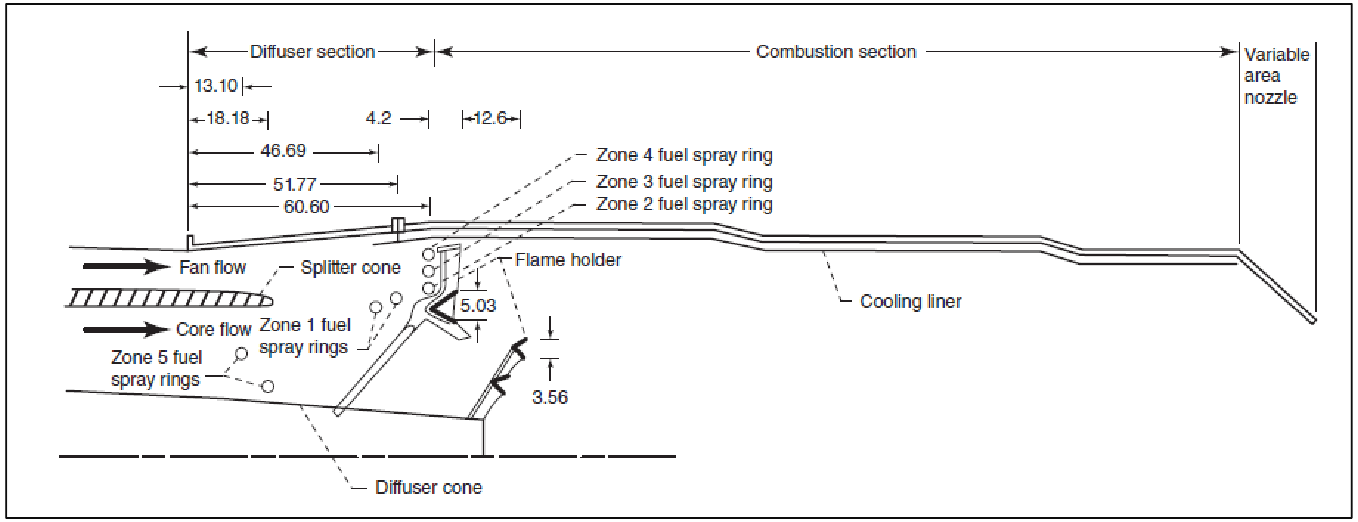


$$\eta_o = \frac{T_{gas} - T_{metal,mean}}{T_{gas} - T_{c,in}}$$

Afterburner Cross Sections



EJ200 afterburner and nozzle



TF30-P-3 afterburner

Effusion Cooling

Effusion Cooling

- Effusion cooling is one of the most promising technique to prevent high metal temperatures on liners.

- Working principle of this technique is to provide thin film layer to hot side of flame tube that covers liners and protects from flame heat load. Moreover, high dense array of effusion holes greatly contributes cooling due to vast heat transfer area increment and high heat transfer coefficient. For instance, a hole drilled at 20° to the liner wall has almost three times the surface area of a hole drilled normal to the wall.

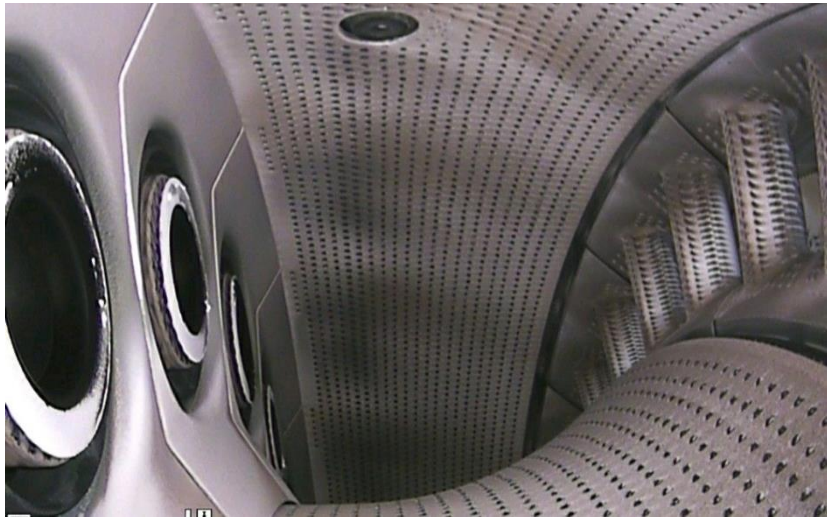
- Full coverage film cooling at turbine stage is very similar with effusion cooling.

Advantages

- Much lower coolant budget need
- Uniform temperature distribution
- Ease of serial production once manufacturing process devepoled

Disadvantages

- Lower strength due to notch effect
- Advanced manufacturing techniques needed



LEAP1A Combustion Chamber

By Ricardo Leon Montoya Cardona [LinkedIn]

HEAT TRANSFER CONTRIBUTIONS OF EFFUSION

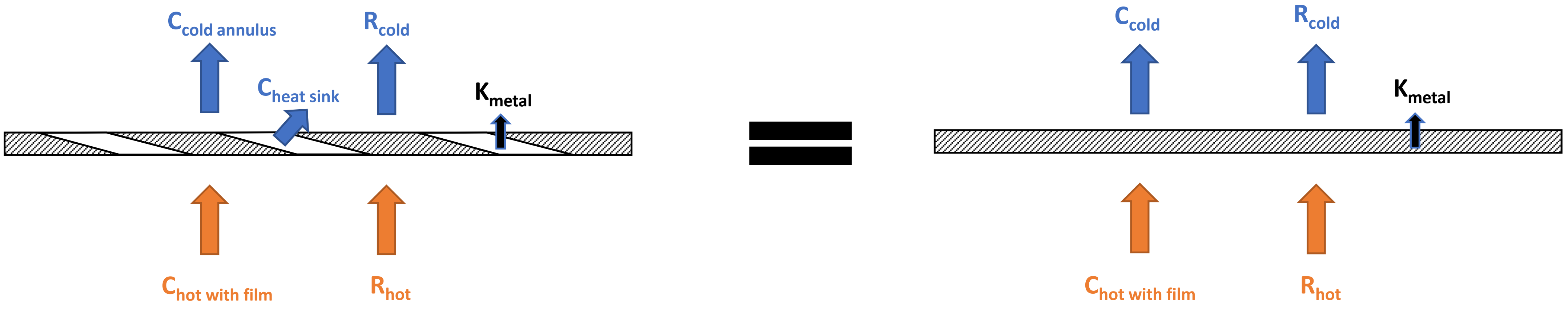
- Gerendas reported Rolls Royce BR715 turbofan engine effusion cooled combustor chamber test and modelling process. They conducted 2D-3D transient thermal analysis and compared with test data. It is revealed;
  - film cooling on hot side **≈30%**
  - internal heat pick-up in effusion holes **≈40%**
  - cold side convection **≈30%**

  contributes heat transfer.

- Andreini conducted tests under non reacting conditions, reported that;
  - film cooling on hot side **≈10-30%**
  - internal heat pick-up in effusion holes **≈45-60%**
  - cold side convection **≈10-20%**

  contributes heat transfer.

SCHEMATIC REPRESENTATION OF HEAT TRANSFER



$$C_{cold} = C_{cold\ annulus} + C_{heat\ sink}$$

- Although it seems we can simply sum annulus and heat sink convections, due to interesting phenomena occurs at cold side downstream of holes, enhancement factor should be added to annulus side convection.

COLD SIDE ENHANCEMENT FACTOR

- The effect can be attributed to the coolant extraction that affects the main flow, generating boundary renewal and local impingement downstream of the effusion cooling hole.

Equations

$$Nu_i = \frac{HTC_{ave;i} \cdot d_h}{\lambda} \qquad Re_{an;i} = \frac{v_{ann;i} \cdot \rho \cdot d_h}{\mu}$$

$$EF = \frac{Nu}{Nu_0} = \frac{Nu}{0.023 \cdot Re^{0.8} \cdot Pr^{0.3}} \qquad SR_i = \frac{v_{eff;i}}{v_{ann;i}}$$

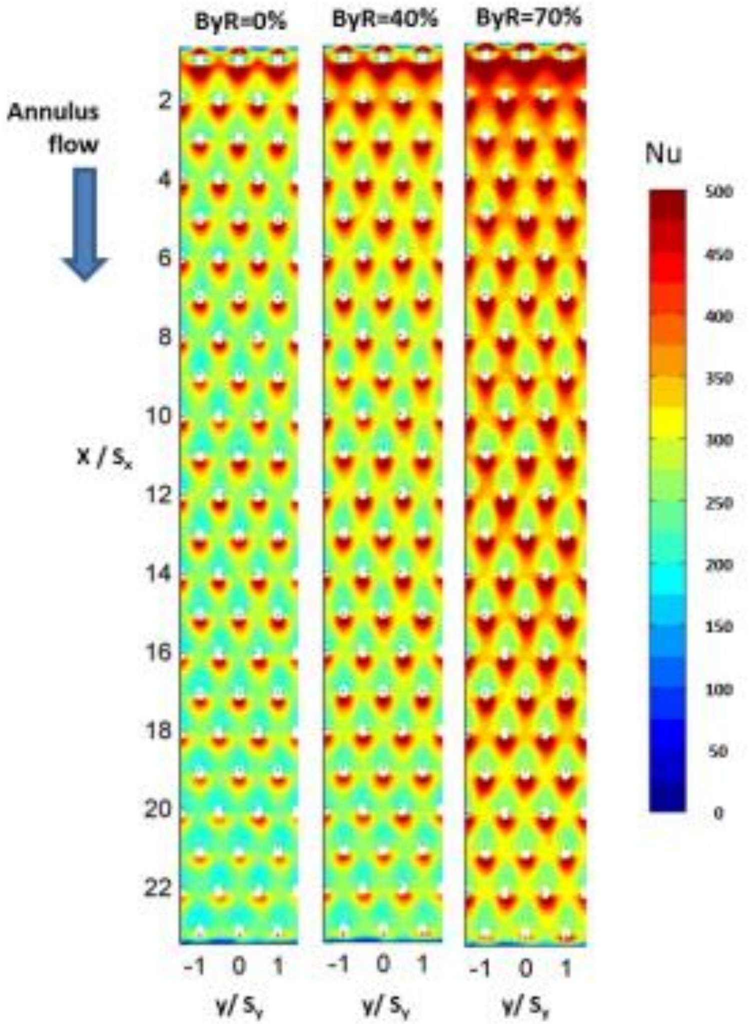
$$EF = 1 + a \cdot Re_{ann}^{b} \cdot SR^{c}$$

$$a = 166.5 \quad b = -0.47 \quad c = 0.40$$

$$HTC_{cs} = \frac{(HTC_{ann} EF area_{ann} + HTC_{hole} area_{holes})}{(area_{ann} + area_{holes})}$$ = Area averaged-combined cold side HTC

$$\mathrm{Area}_{\mathrm{cs}} = \mathrm{Area}_{\mathrm{holes}} + \mathrm{Area}_{\mathrm{ann}}$$

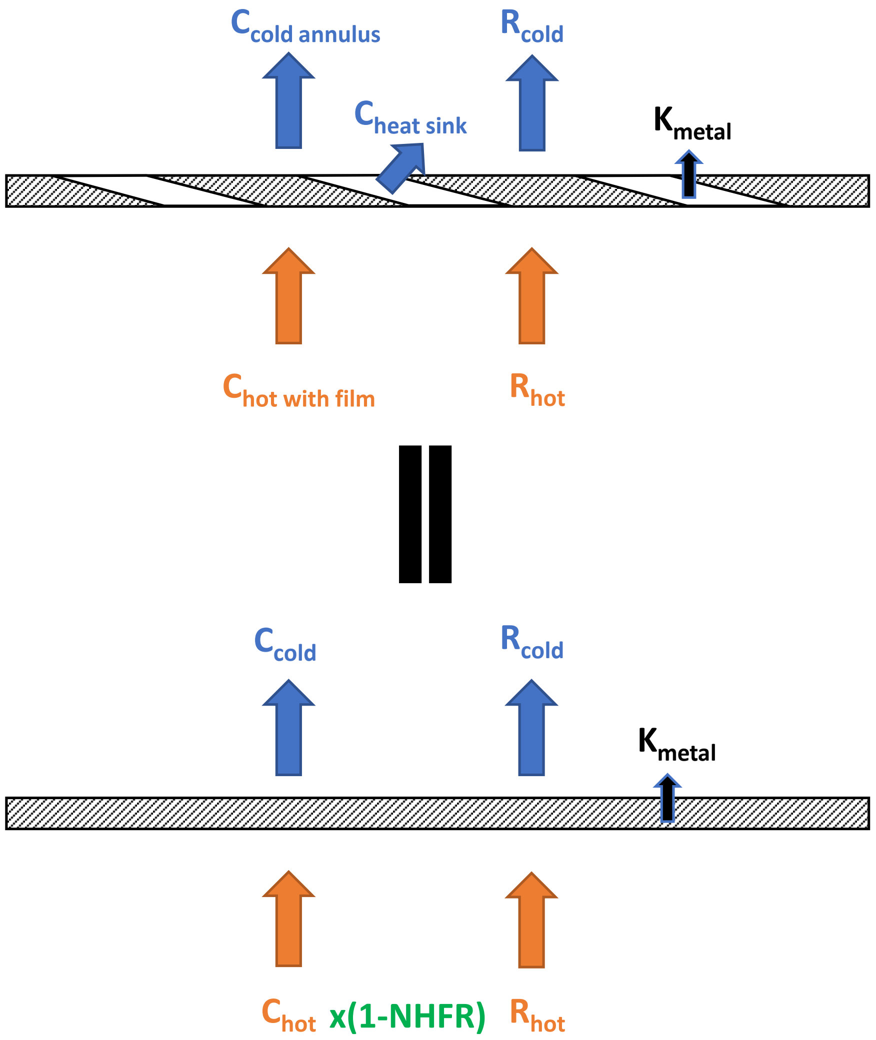
cs: cold side
ann: annulus



Enhancement factor distribution from Andreini(2016)

- For further reading;
  - Andreini, A., Becchi, R., Facchini, B., Mazzei, L., Picchi, A., & Peschiulli, A. (2016, June). Effusion Cooling System Optimization for Modern Lean Burn Combustor. In Turbo Expo: Power for Land, Sea, and Air (Vol. 49798, p. V05BT17A015). American Society of Mechanical Engineers
  - Byerley, A. R., Jones, T. V., & Ireland, P. T. (1992, June). Internal cooling passage heat transfer near the entrance to a film cooling hole: Experimental and computational results. In Turbo Expo: Power for Land, Sea, and Air (Vol. 78965, p. V004T09A021). American Society of Mechanical Engineers

1D CALCULATION METHODS - NHFR



$C_{cold\ annulus}$ $C_{heat\ sink}$ R_{cold} K_{metal}

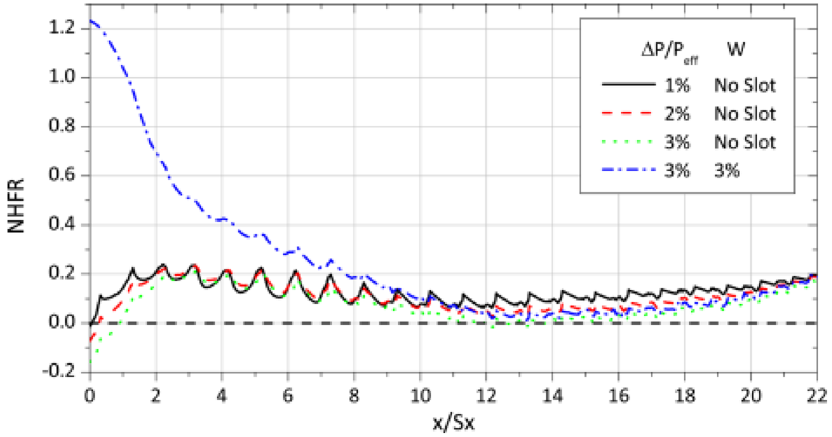
$C_{hot\ with\ film}$ R_{hot}

C_{cold} R_{cold} K_{metal}

C_{hot} x(1-NHFR) R_{hot}

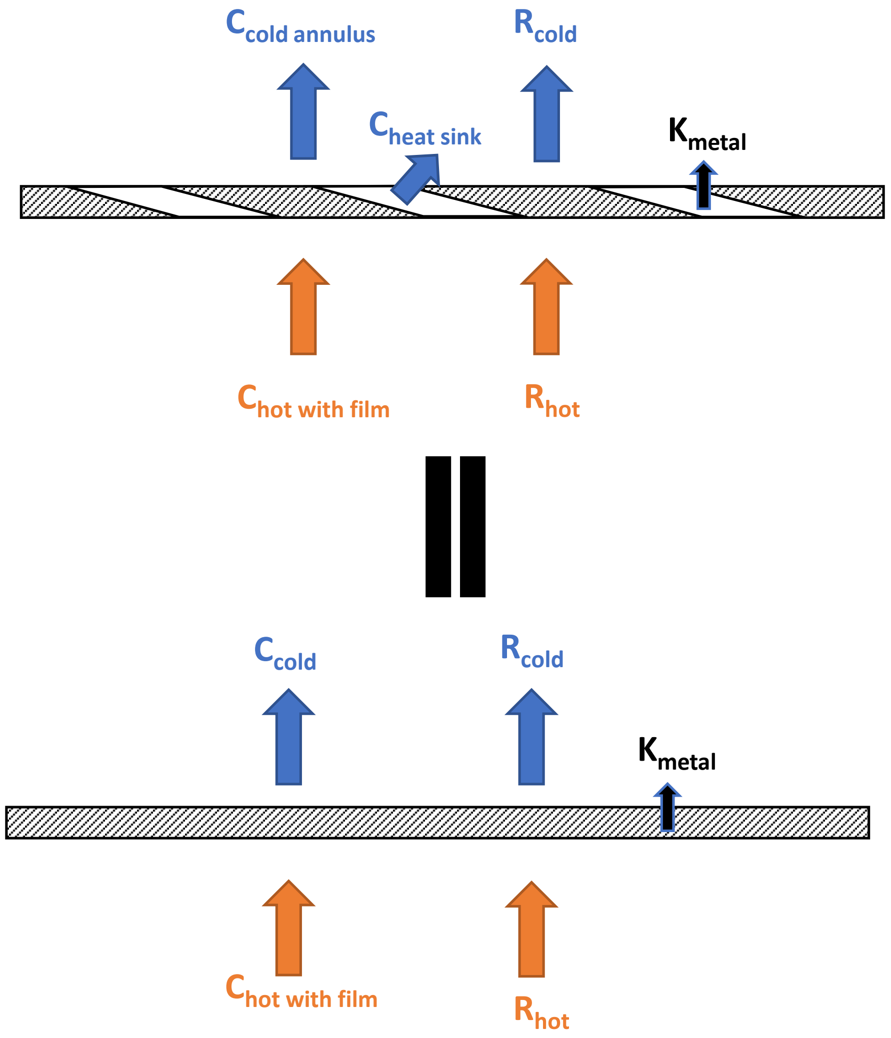
- NHFR: Net Heat Flux Reduction: Heat transfer profit because of film layer
- Constant NHFR (from literature)
- In order to reach target metal temperature, pressure difference, thus coolant mass flow rate should be altered and optimized.

$$NHFR = 1 - q''/q''_0 = 1 - \frac{h_f(T_{aw} - T_w)}{h_0(T_\infty - T_w)}$$



Laterally averaged NHFR distribution from Andreini

1D CALCULATION METHODS



- Variable adiabatic film effectiveness.
- In order to reach target metal temperature, pressure difference, thus coolant mass flow rate should be altered and optimized.
- Either full coverage film cooling correlations should be employed or simple adiabatic film effectiveness correlations should be used with superposition.

$$\eta_s = \sum_{i=1}^{n} \eta_i \prod_{j=0}^{i-1} (1-\eta_j) \quad \text{where } \eta_0 = 0$$

Superposition of film effectiveness

Sellers (1963)

For further reading;

- Dutta, Sandip Ekkad, Srinath Han, Je-Chin - Gas Turbine Heat Transfer and Cooling Technology, Second Edition-CRC Press (2012)- Chapter 3: Turbine Film Cooling

OVERALL COOLING EFFECTIVENESS

Overall Cooling Effectiveness of Effusion Cooled Annular Combustor Liner at Reacting Flow Conditions (Ji-2018, Shanghai Jiaotong University)

- A three-sector annular combustor test rig is built to carry out experimental investigation on the liner effusion cooling performance using steady state infrared radiation thermography method at reacting flow conditions.
- 7 rows of effusion holes.
- Coolant-to-main air flow rate ratio and equivalence ratio are varied to evaluate their effects on the cooling effectiveness.
- Results for effusion holes in different inclination angle (90° and 30°) are compared.

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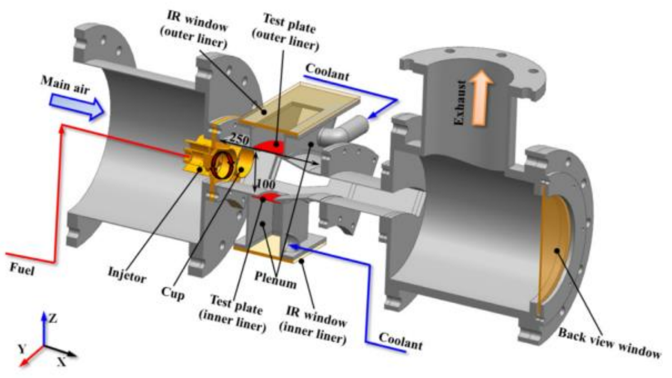


Fig. 1. Sketch of experimental system.

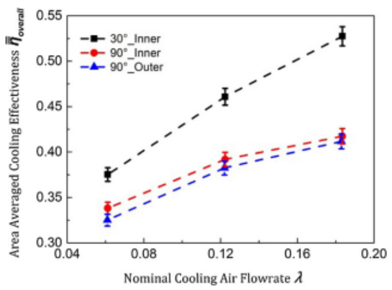


Fig. 13. Effect of flowrate on area average cooling effectiveness.

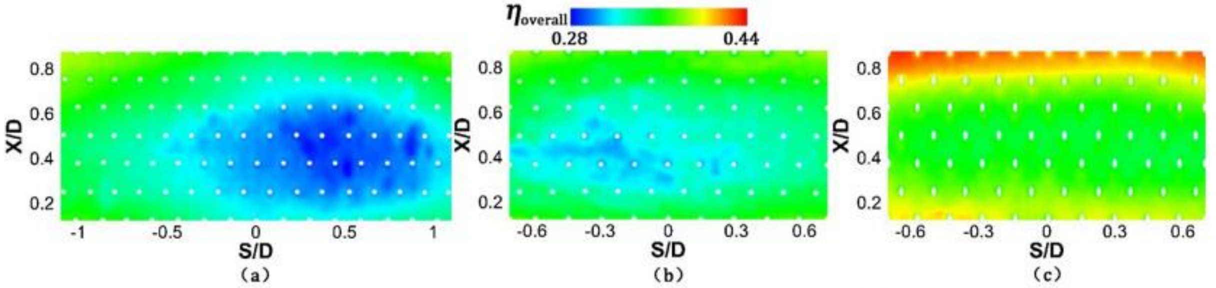


Fig. 8. Overall cooling effectiveness distribution at $\lambda = 6\%, \Phi = 0.9$: (a) G1; (b) G2; (c) G3.

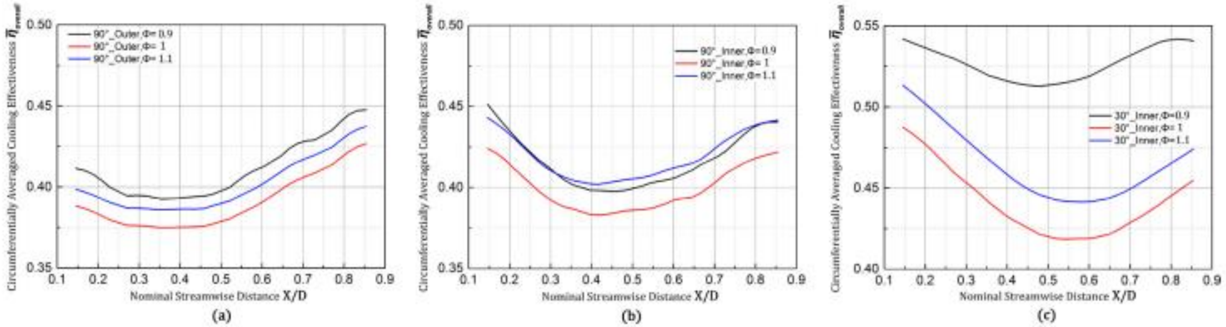
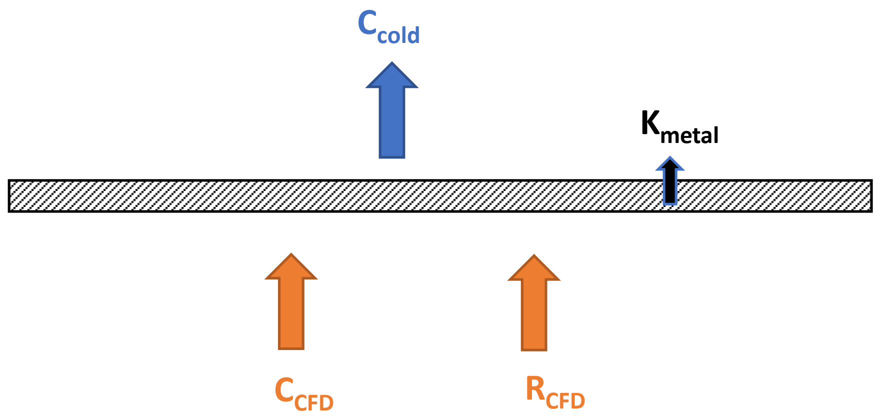


Fig. 16. Effect of equivalence ratio on circumferentially averaged cooling effectiveness: (a) G1; (b) G2; (c) G3.

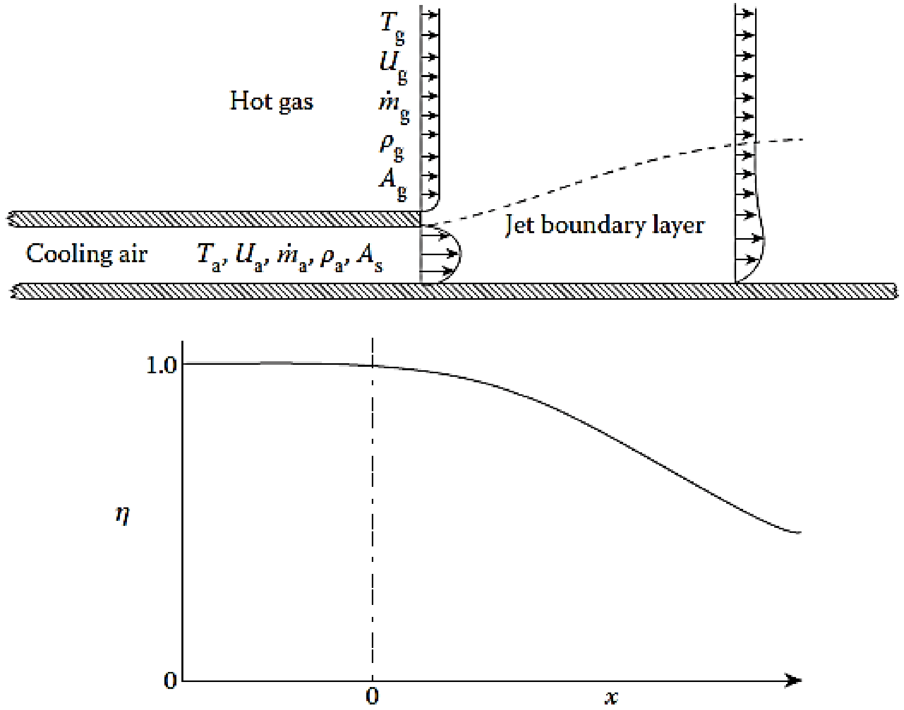
3D THERMAL ANALYSIS

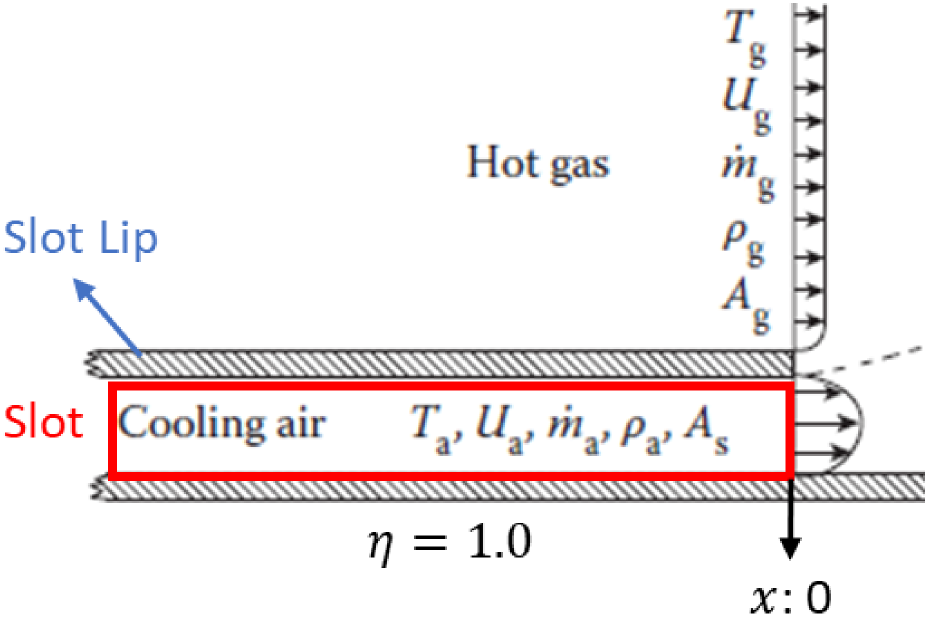
- CFD tools can be benefited while conducting 3D thermal analysis.
- There is tricky way to obtain 3D temperatures
- 2 simple steps of analysis are;
    1. Define cold side HTC to cold side of the liner
    2. Define metal thickness to the liner, it will provide you to carry out analysis without solid-metal mesh.
- CFD tool will solve the node temperature with radial conduction, whereas axial and tangential conduction won't be considered. It will lead to higher node temperatures, however 3D metal temperatures will be obtained in very simple and quick way.



Cooling Design – Film Cooling

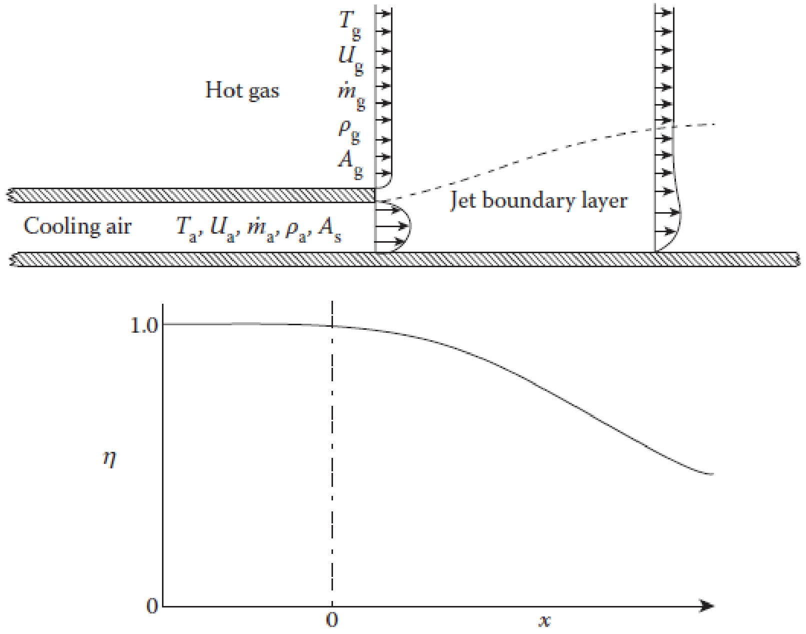
Film cooling is very effective cooling method which reduces the hot gas adiabatic wall temperature by mixing the cooling air and hot gas. This mixed gas covers the surface and becomes the new adiabatic wall temperature (T_{aw}) which drives the heat transfer. The adiabatic wall temperature coming from film injection is between the hot gas (T_g) and cooling air (T_a) temperatures and increases with downstream distance from the coolant injection due to continuous mixing.





Cooling Design – Film Cooling

Cooling air is injected to a slot, which is separated from hot gas region by a lip. The slot prevents the cooling gas penetration to hot gas by breaking the radial velocity component of cooling air and provides the cooling air velocity has only axial velocity component. Almost all the theoretical and experimental studies of film cooling carried out so far have been aimed at finding geometric and flow parameters to describe the temperature of an adiabatic wall at any point downstream of the coolant injection. For film adiabatic wall temperature calculations, the correlations in next pages can be used.



$$\eta = \frac{T_g - T_{aw}}{T_g - T_a} \qquad m = \frac{\rho_a U_a}{\rho_g U_g}$$

For 0.5 < m < 1.3:

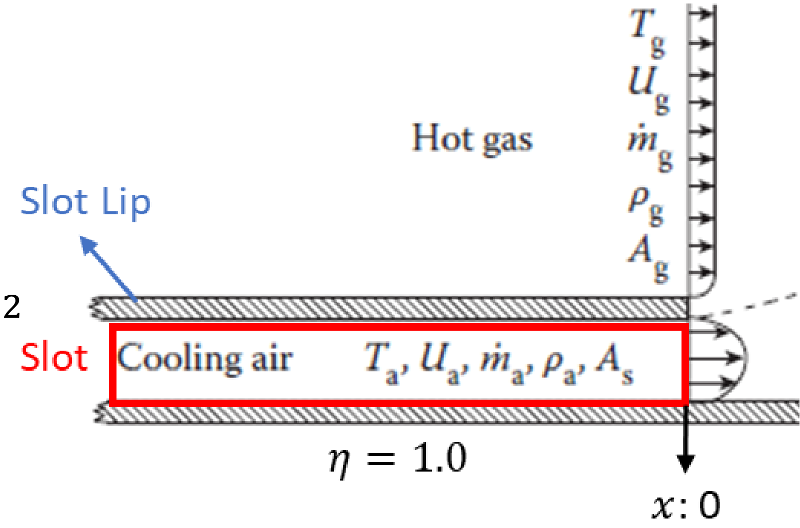
$$\eta = 1.1 m^{0.65} \left(\frac{\mu_a}{\mu_g}\right)^{0.15} \left(\frac{x}{s}\right)^{-0.2} \left(\frac{t}{s}\right)^{-0.2}$$

For 1.3 < m < 4.0:

$$\eta = 1.28 \left(\frac{\mu_a}{\mu_g}\right)^{0.15} \left(\frac{x}{s}\right)^{-0.2} \left(\frac{t}{s}\right)^{-0.2}$$

Inside the slot:

$$\eta = 1.0$$



m: mass velocity / blowing ratio
s: slot height, [m]
t: slot lip thickness, [m]
x: distance downstream of slot, [m]
η: Film cooling effectiveness
μ: dynamic viscosity, [kg/(ms)]

Closing Remarks

Key Points for Teknofest

- Right *material selection based* on worst case thermals. Worst case must be examined with the effects of cooling, combustion and radiation.
- Feedback to mechanical design based on thermal results
  - Temperature distribution of designed parts
- 2D thermal data both for casing and liner. (2D temperature distributions can be calculated)

TUSAŞ MOTOR SANAYİİ A.Ş.
TUSAŞ ENGINE INDUSTRIES, INC.

THANK YOU

Any Questions?

REFERENCES

1) Andreini, A., Becchi, R., Facchini, B., Mazzei, L., Picchi, A., & Turrini, F. (2016). Adiabatic effectiveness and flow field measurements in a realistic effusion cooled lean burn combustor. Journal of Engineering for Gas Turbines and Power, 138(3)
2) Andreini, A., Becchi, R., Facchini, B., Mazzei, L., Picchi, A., & Peschiulli, A. (2016, June). Effusion Cooling System Optimization for Modern Lean Burn Combustor. In Turbo Expo: Power for Land, Sea, and Air (Vol. 49798, p. V05BT17A015). American Society of Mechanical Engineers
3) Andreini, A., Facchini, B., Becchi, R., Picchi, A., & Turrini, F. (2016). Effect of slot injection and effusion array on the liner heat transfer coefficient of a scaled lean-burn combustor with representative swirling flow. Journal of Engineering for Gas Turbines and Power, 138(4)
4) Gerendás, M., Höschler, K., & Schilling, T. (2003). Development and modeling of angled effusion cooling for the BR715 low emission staged combustor core demonstrator. BMW ROLLS-ROYCE GMBH DAHLEWITZ (GERMANY).
5) Dutta, Sandip Ekkad, Srinath Han, Je-Chin - Gas Turbine Heat Transfer and Cooling Technology, Second Edition-CRC Press (2012)- Chapter 3: Turbine Film Cooling
6) Ji, Y., Ge, B., Chi, Z., & Zang, S. (2018). Overall cooling effectiveness of effusion cooled annular combustor liner at reacting flow conditions. Applied Thermal Engineering, 130, 877-888

Examples

Heat Transfer of Luminous Gases with Film Cooling

When a hydrocarbon fuel is burned in a afterburner, soot particles are formed; these particles have an important effect on the nature of the radiation from the flame. At atmospheric pressure, the soot particles are too small in number and size to radiate appreciable energy. However, some of the radiation from these hot, glowing particles falls in the visible spectrum and gives rise to the name “luminous flame.” With increasing pressure, the luminous radiation increases in intensity, and the banded spectra from water vapor and carbon dioxide become less pronounced. At the high levels of pressure encountered in modern gas turbines, the soot particles can attain sufficient size and concentration to radiate as black-bodies in the infrared region, and the flame is then characterized by a predominance of luminous radiation. It is under these conditions that severe radiant heating and its attendant problem of liner durability are encountered

Internal and External Radiation

$$R_1 = 0.5\sigma(1+\varepsilon_w)\varepsilon_g T_g^{1.5}\left(T_g^{2.5} - T_{w_1}^{2.5}\right)$$

$$\varepsilon_g = 1 - \exp\left[-290PL(ql_b)^{0.5}T_g^{-1.5}\right].$$

$$L = 336/H^2$$

$$l_b = 0.6D_L$$

H: fuel hydrogen content (by mass)

lb: beam length [m]
q: fuel/air ratio (by mass)
P: pressure [kPa]

$$R_2 = \sigma\frac{\varepsilon_w\varepsilon_c}{\varepsilon_c + \varepsilon_w(1-\varepsilon_c)(A_w/A_c)}\left(T_{w_2}^4 - T_3^4\right).$$

w: liner
c: casing
3: coolant

Aw/Ac = liner diameter/casing diameter

Internal and External Convection

$$C_1 = 0.020\frac{k_g}{d_{h1}^{0.2}}\left(\frac{\dot{m}_g}{A_L\mu_g}\right)^{0.8}(T_g - T_{w_1})$$

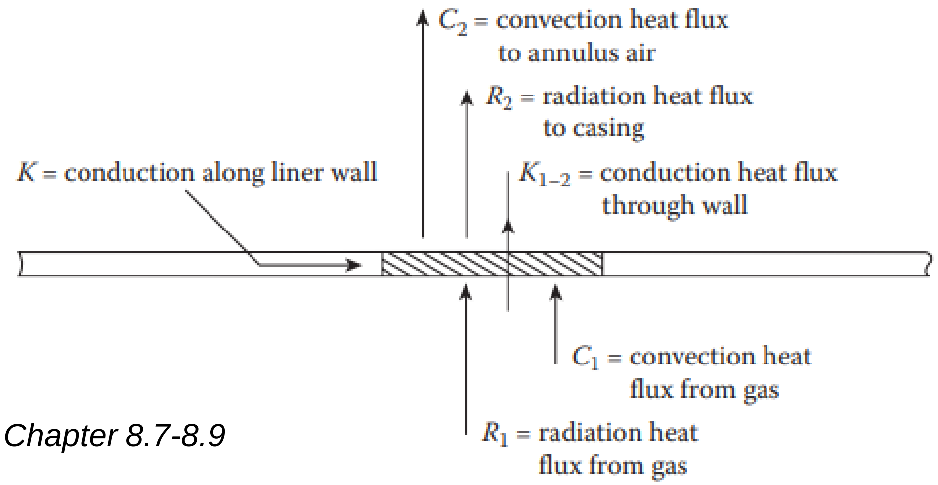
$$d_{h1} = 4\frac{\text{Cross-sectional flow area}}{\text{Wetted perimeter}} = D_L.$$

$$C_2 = 0.020\frac{k_a}{D_{an}^{0.2}}\left(\frac{\dot{m}_{an}}{A_{an}\mu_a}\right)^{0.8}(T_{w_2} - T_3).$$

$$D_{an} = 4\frac{\text{Cross-sectional area of flow}}{\text{Wetted perimeter}}$$

Energy Balance

$$R_1 + C_1 = R_2 + C_2 = \frac{k_w}{t_w}(T_{w_1} - T_{w_2}) = K_{1-2}.$$

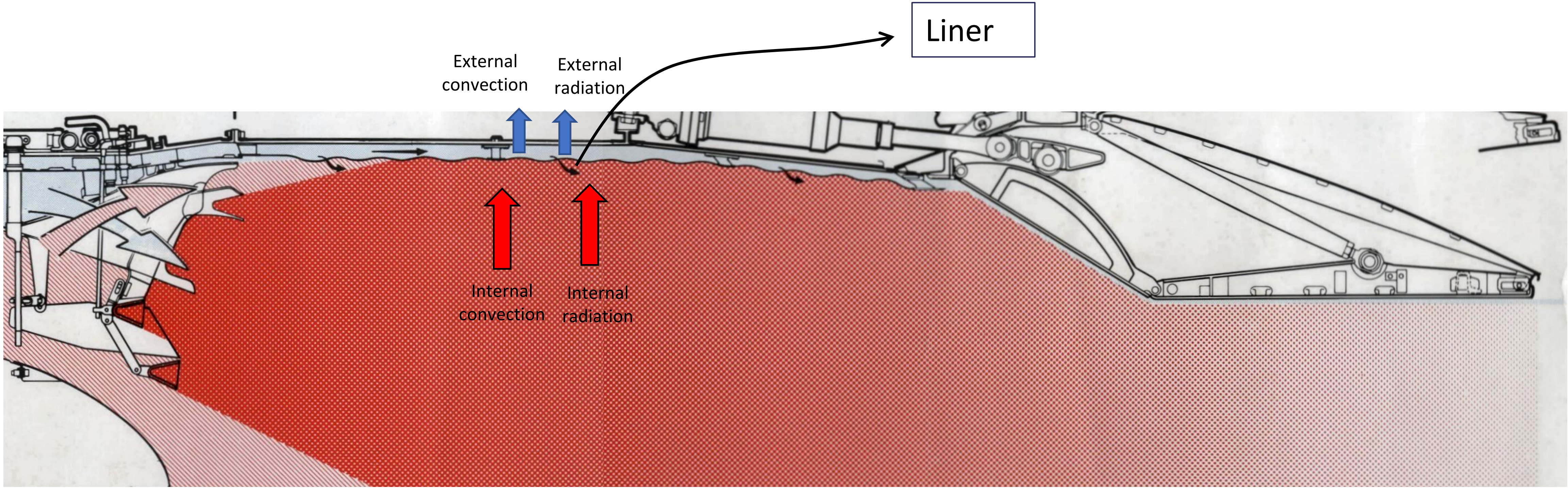


Example is taken from Gas Turbine Combustion Alternative Fuels and Emissions (Lefebvre-3rd Edition) – Chapter 8.7-8.9
For further reading, please get the book.

Heat Transfer of Luminous Gases with Film Cooling

F110-GE Engine Afterburner

Internal convection + Internal radiation = Metal conduction = External convection + External radiation



Heat Transfer of Luminous Gases with Film Cooling Example

- We wish to estimate the liner-wall temperature that could be expected in the primary zone of a tubular combustor if film cooling was used, given the following information.
- P3 = 30 atm = 3040 kPa
- T3 = 880 K
- Tg = 2280 K
- Casing diameter = 0.192 m
- Liner outer diameter = 0.1344 m
- Liner wall thickness = 0.0012 m
- Liner inner diameter = 0.132 m
- ε_c = 0.4 (aluminum casing)
- ε_w = 0.7 (Nimonic 75 liner material)
- k_w = 26 W/(m K)
- m_{an} = 7.074 kg/s
- m_{pz} = 2.62 kg/s
- q_{pz} = 0.0588
- L = 1.7 (kerosine fuel)

- Calculate liner temperature at downstream of film cooling slot, where x/s: 18
- t/s, s and As are given next page.

Example is taken from Gas Turbine Combustion Alternative Fuels and Emissions (Lefebvre-3rd Edition) – Chapter 8.7-8.9
For further reading, please get the book.

Heat Transfer of Luminous Gases with Film Cooling Example Con’t

Internal Radiation

$$\sigma = 5.67\times10^{-8}\ \mathrm{W/(m^2\cdot K^4)},$$

$$\varepsilon_w = 0.7,$$

$$T_g = 2280\,\mathrm{K},$$

$$L = 1.7,$$

$$P = 3040\,\mathrm{kPa},$$

$$q = 0.0588,$$

$$l_b = 0.6D_L = 0.0792\,\mathrm{m}.$$

$$\varepsilon_g = 0.61 \text{ and } R_1 = 794460 - 0.0032T_{w_1}^{2.5}\ \mathrm{W/m^2}.$$

Step 1. Flame induced radiation heat load shall be calculated. Unlike metals, emissivity coefficient of hot gas is highly dependent on pressure and fuel mixture.

External Radiation

$$\sigma = 5.67\times10^{-8}\ \mathrm{W/(m^2\cdot K^4)},$$
$$\varepsilon_w = 0.7,$$
$$\varepsilon_c = 0.4,$$
$$D_L/D_{ref} = 0.1344/0.192 = 0.7,$$
$$T_c = T_3 = 880\,\mathrm{K}.$$

$$\boxed{R_2 = 2.29\left(\frac{T_{w_2}}{100}\right)^4 - 13{,}715\ \mathrm{W/m^2},}$$

Step 2. External radiation shall be calculated. In order to simplify problem, it is assumed casing temperature is same with coolant temperature.

Internal Convection

$$\frac{x}{s} = 18 \quad \frac{t}{s} = 0.4 \quad s = 0.00145\,\mathrm{m},$$

$$A_s = \pi D_L S = 5.95\times10^{-4}\,\mathrm{m^2}.$$

$$x = 18\times0.00145 = 0.0261\,\mathrm{m},$$

$$\dot m_s = \rho_a U_a A_s = 0.289\,\mathrm{kg/s}.$$

$$\rho_a U_a = 485.7\,\mathrm{kg/(m^2\cdot s)}.$$

$$\mu_a = 3.89\times10^{-5}\,\mathrm{kg/(m\cdot s)},$$

$$k_a = 0.0553\,\mathrm{W/(m\cdot K)}.$$

$$\mathrm{Re}_s = \frac{\rho_a U_a s}{\mu_a} = 1.81\times10^4,$$

$$\mathrm{Re}_x = \frac{\rho_a U_a x}{\mu_a} = 3.26\times10^5.$$

$$A_L = 0.0137\,\mathrm{m^2},$$

$$T_g = 2280\,\mathrm{K},$$

$$\mu_g = 7.05\times10^{-5}\,\mathrm{kg/(m\cdot s)},$$

$$q_{pz} = 0.05,$$

$$\dot m_g = \rho_g U_g A_L = 2.62\,\mathrm{kg/s},$$

$$k_g = 0.157\,\mathrm{W/(m\cdot K)}.$$

$$\rho_g U_g = \frac{2.62}{0.137} = 191\,\mathrm{kg/(m^2\cdot s)}.$$

$$m = \frac{\rho_a U_a}{\rho_g U_g} = \frac{485.7}{191} = 2.54.$$

$$\eta = 1.28\left(\frac{\mu_a}{\mu_g}\right)^{0.15}\left(\frac{xt}{s^2}\right)^{-0.2} = 1.28\left(\frac{3.89}{7.05}\right)^{0.15}(18\times0.4)^{-0.2} = 0.789.$$

$$\eta = \frac{T_g - T_{w,ad}}{T_g - T_a} = \frac{2280 - T_{w.ad}}{2280 - 880}.$$

$$\boxed{T_{w,ad} = 1176\ \mathrm{K}.}$$

$$\boxed{\begin{aligned} C_1 &= 0.10\frac{k_a}{x}(\mathrm{Re}_x)^{0.8}\left(\frac{x}{s}\right)^{-0.36}(T_{w,ad} - T_{w1}) \\ &= 0.10\frac{0.157}{0.0261}(3.26\times10^5)^{0.8}18^{-0.36}(1176 - T_{w1}) \\ &= 1926(1176 - T_{w1})\,\mathrm{W/m^2}. \end{aligned}}$$

Step 3. Since liners are cooled with film cooling, film cooling effectiveness and heat transfer coefficient of hot side shall be calculated respectively. These 2 value will determine internal convection heat load.

Example is taken from Gas Turbine Combustion Alternative Fuels and Emissions (Lefebvre-3rd Edition) – Chapter 8.7-8.9   For further reading, please get the book.

Heat Transfer of Luminous Gases with Film Cooling Example Con't

External Convection

$$C_2 = 0.020 \frac{k_a}{D_{an}^{0.2}} \left(\frac{\dot{m}_{an}}{A_{an} \mu_a} \right)^{0.8} (T_{w_2} - T_3),$$

$$T_c = T_3 = 880\,\mathrm{K},$$

$$k_a = 0.0553\,\mathrm{W/(m \cdot K)},$$

$$\mu_a = 3.89 \times 10^{-5}\,\mathrm{kg/(m \cdot s)},$$

$$\dot{m}_{an} = 7.074\,\mathrm{kg/s},$$

$$A_{an} = (\pi/4)(0.192^2 - 0.1344^2) = 0.01476\,\mathrm{m}^2,$$

$$A_{an} = 0.192 - 0.1344 = 0.0576\,\mathrm{m}.$$

$$\boxed{C_2 = 291(T_{w_2} - 880) = 921 T_{w_2} - 810{,}480\ \mathrm{W/m^2}.}$$

Step 4. External convection heat load shall be calculated. Casing temperature assumption is applied again.

Metal Conduction

$$\boxed{K_{1-2} = \frac{26}{0.0012}(T_{w_1} - T_{w_2}) = 21{,}667(T_{w_1} - T_{w_2}).}$$

Step 5. Metal conduction shall calculated.

Result

$$R_1 = 794{,}460 - 0.0032 T_{w1}^{2.5}\ \mathrm{W/m^2},$$

$$R_2 = 2.29 \left(\frac{T_{w2}}{100} \right)^4 - 13{,}715\,\mathrm{W/m^2},$$

$$C_2 = 921 T_{w2} - 810{,}400\,\mathrm{W/m^2},$$

$$K_{1-2} = 21{,}667(T_{w1} - T_{w2}).$$

$$\boxed{T_{w1} = 1283\,\mathrm{K} \quad T_{w2} = 1265\,\mathrm{K}.}$$

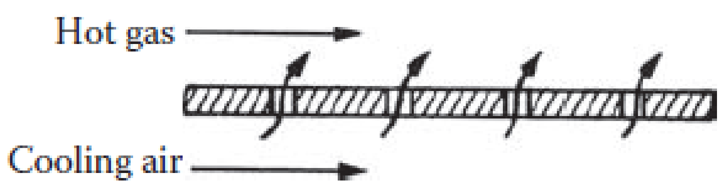
Step 6. Since all heat loads are calculated, heat balance can be set and than Tw1 and Tw2 can be determined.

Example is taken from Gas Turbine Combustion Alternative Fuels and Emissions (Lefebvre-3rd Edition) – Chapter 8.7-8.9
For further reading, please get the book.

Cooling Design – Effusion Cooling

The physics is same with film cooling. The difference is that the cooling air is injected into the hot gas directly with a radial velocity component without any slot structure. For film adiabatic wall temperature calculations, the correlations below can be used.

$$\overline{\eta}=f\left(M,P,Tu,\frac{x}{D},\alpha,\frac{s}{D},\frac{\delta_1}{D},\frac{L}{D}\right)$$



$$\overline{\eta}=\eta_c\frac{DR^{0.9/\frac{P}{D}}}{(sin\alpha)^{0.06\frac{P}{D}}}$$

1

$$\eta_c=\frac{\eta_{c0}\eta^*\left(\frac{\mu}{\mu_0}\right)^a}{\left[1+\left(\frac{\mu}{\mu_0}\right)^{(a+b)c}\right]^{1/c}}\qquad \eta_{c0}=\frac{0.465}{1+0.048\left(\frac{P}{D}\right)^2}$$

2

$$\mu=U\cdot DR^{0.8}\left(1-\left[0.03+0.11\left(5-\frac{P}{D}\right)\right]cos\alpha\right)\qquad \mu_0=0.125+0.063\left(\frac{P}{D}\right)^{1.8}$$

3

$$a=0.2$$

$$b=exp\left[1.92-7.5\left(\frac{P}{D}^{(-1.5)}\right)\right]$$

$$c=0.7+336e^{\left(-1.85\frac{P}{D}\right)}$$

$$b_1=\frac{b_0}{1+M^{-3}}$$

$$c_1=7.5+\frac{P}{D}$$

4

$$\eta^*=0.1\left(\frac{\eta^{*\prime}}{0.1}\right)^{1/\eta_s}\left[1+\left(\frac{\xi'}{\xi_1}\right)^{b_1c_1}\right]^{1/c_1}\qquad \eta^{*\prime}=\frac{\eta_{0T}\left(\frac{\xi'}{\xi_0}\right)^{a^*}}{\left[1+\left(\frac{\xi'}{\xi_0}\right)^{(a^*+b_T^*)c^*}\right]^{1/c^*}}\qquad \eta_s=1+\frac{\hat{\eta}}{1+\left(\frac{U\cdot DR^g}{k}\right)^{-5}}$$

ξ_0	η_0	a^*	c^*
9	5.8	4	0.24

5

$$\hat{\eta}=0.022\left(\frac{P}{D}+1\right)(0.9-sin2\alpha)-\left[0.08+\frac{0.46}{1+\left(\frac{P}{D}-3.2\right)^2}\right]\qquad k=2\left[1-e^{0.57\left(1-\frac{P}{D}\right)}\right]+0.91cos^{0.65}\alpha\qquad \eta_{0T}=2.5\left(\frac{5.8}{2.5}\right)^{\frac{b_T^*}{0.7}}$$

Cooling Design – Effusion Cooling: Con’t

$$\xi_1 = \frac{65}{\left(\frac{M}{2.5}\right)^{a_1}} \qquad \xi' = \xi^{\xi_s} \qquad \xi_s = 1 + \frac{\hat{\xi}}{1 + \left(\frac{U \cdot DR^g}{k}\right)^{-5}} \qquad \hat{\xi} = 1.17\left[1 - \frac{\left(\frac{P}{D} - 1\right)}{1 + 0.2\left(\frac{P}{D} - 1\right)^2}\right](cos2.3\alpha + 2.45) \qquad \xi = \frac{\frac{x}{D}\frac{P}{D}\xi_c}{\frac{\pi}{4}U\left(\frac{P}{D}/3\right)^{-0.75}}$$

6

$$\xi_c = 0.6 + \frac{0.4\,(2 - cos\alpha)}{1 + \left(\frac{P/D - 1}{3.3}\right)^6} \qquad a_1 = 0.04 + 0.23\left(\frac{P}{D}\right)^2 + \left(1.5 - \frac{2}{\sqrt{\frac{P}{D}}}\right) sin\left(0.86\alpha\left[1 + \frac{0.754}{1 + 0.87\left(\frac{P}{D}\right)^2}\right]\right) \qquad g = 0.75\left[1 - e^{-0.8\left(\frac{P}{D} - 1\right)}\right]$$

$$b_T^* = 0.7\left(1 + \left[\frac{1.22}{1 + 7\left(\frac{P}{D} - 1\right)^{-7}} + 0.87 + cos2.5\alpha\right] * e^{\left[2.6Tu - \frac{0.0012}{Tu^2} - 1.76\right]}\right]$$

$$b_0 = 0.8 - 0.014\left(\frac{P}{D}\right)^2 + \left(1.5 - \frac{2}{\sqrt{\frac{P}{D}}}\right) sin\left(0.86\alpha\left[1 + \frac{0.754}{1 + 0.87\left(\frac{P}{D}\right)^2}\right]\right)$$

7

8

$$\frac{x}{D} = \frac{\xi'^{\,1/\xi_s}\frac{\pi}{4}U\left(\frac{P}{D}/3\right)^{-0.75}}{\frac{P}{D}\xi_c}$$

9

$$\overline{\eta} = \eta_c \frac{DR^{0.9/\frac{P}{D}}}{(sin\alpha)^{0.06\frac{P}{D}}}$$

ξ_0	η_0	a^*	c^*
9	5.8	4	0.24

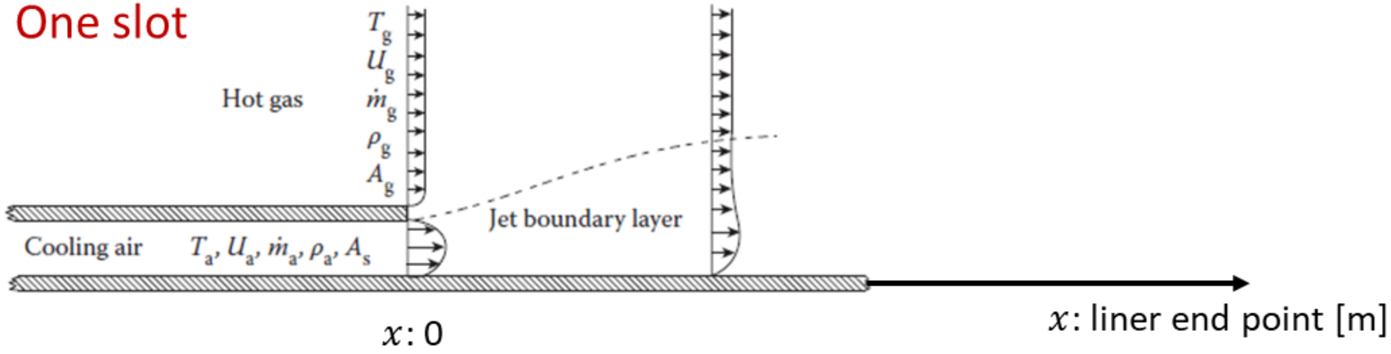
DR: density ratio
x: distance downstream of slot
P: effusion hole spacing

η: Film cooling effectiveness
Tu: turbulence intensity
α: injection angle
D: hole diameter

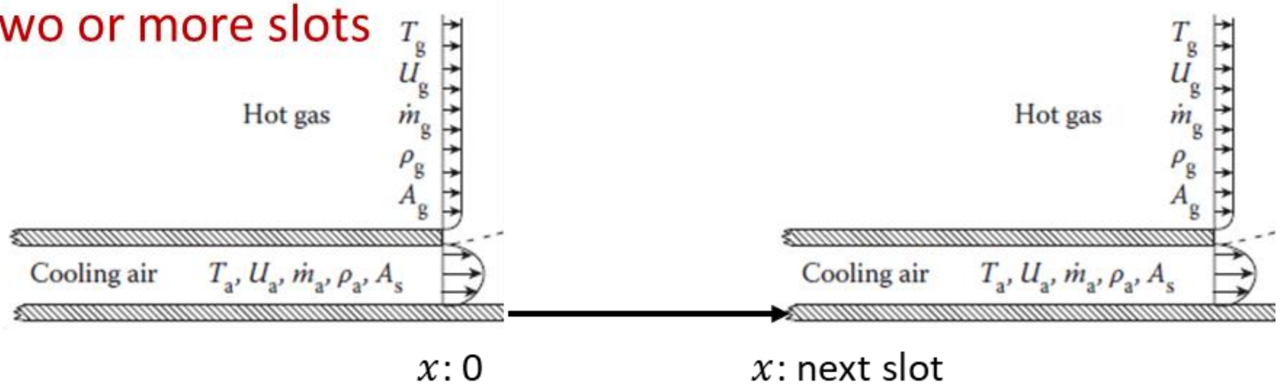
Cooling Design – Application: Film Cooling

- One slot: Effectiveness will be taken as 1.0 in the slot and 20 locations will be calculated from slot end point (x = 0) to liner end point (exhaust location). Then, these 20 points will be averaged and taken as area average adiabatic wall temperature.
  Two or more slots: Effectiveness will be taken as 1.0 in the slot and 5 locations will be calculated from slot end point (x = 0) to next slot. Then, these 5 points will be averaged and taken as area average adiabatic wall temperature.

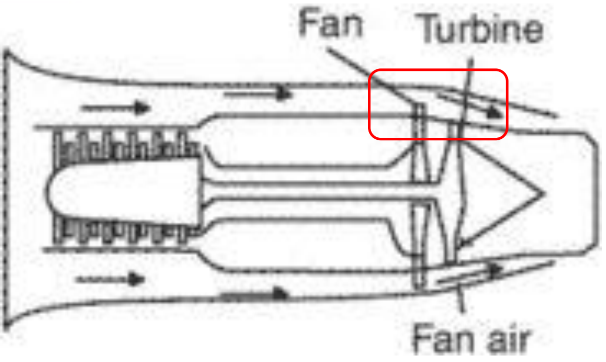
One slot

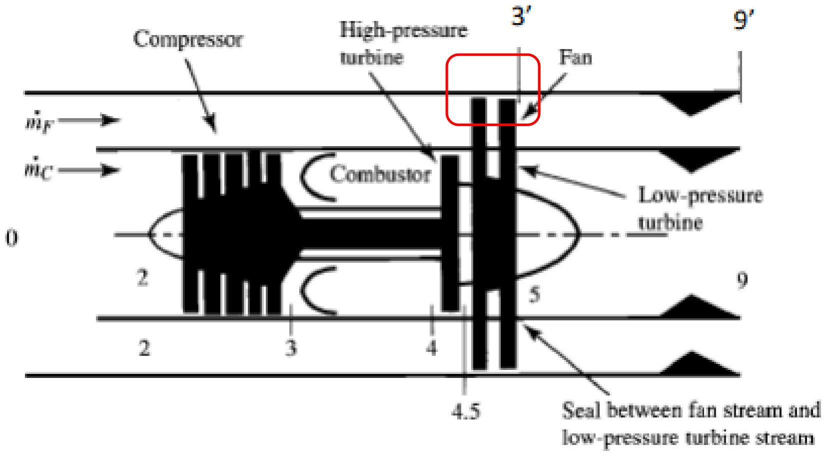


Two or more slots

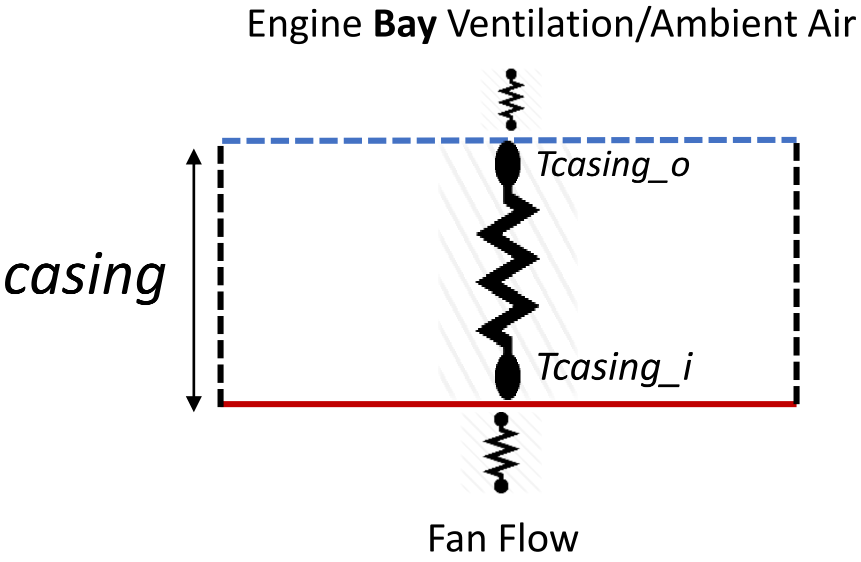


1D Heat Transfer Calculations of Casing





A_bay	m2	0.035814
HTC_bay	W/m2K	150
T_bay	K	350
k_casing	W/mK	150
A_fan	m2	0.034872
HTC_fan	W/m2K	550
T_fan	K	400
Q, total	W	207.37
Tcasing_o		388.6011
Tcasing_i		389.1879



Engine **Bay** Ventilation/Ambient Air

Tcasing_o

casing

Tcasing_i

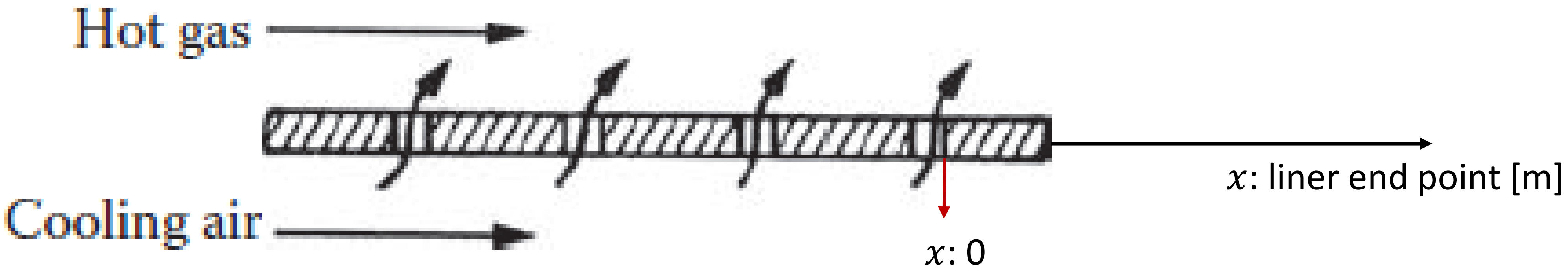
Fan Flow

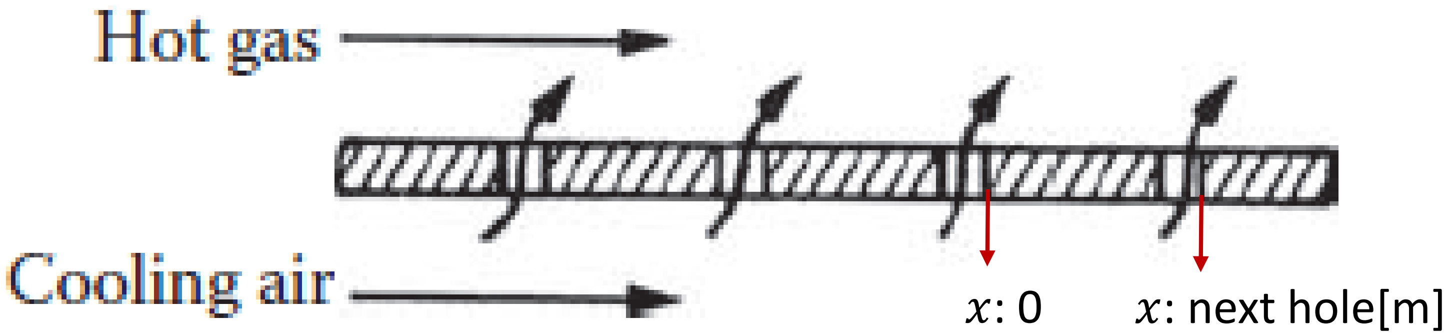
**the values are arbitrary.*
The geometry, dimensions, materials,
Cooling technique (HTC-correlations), air temperatures may change with respect to your own design.

Cooling Design – Application: Effusion Cooling

One hole: 20 locations will be calculated from hole injection point (x = 0) to liner end point (exhaust location). Then these 20 points will be averaged and taken as area average adiabatic wall temperature.

Two or more holes: 5 locations will be calculated from slot end point (x = 0) to next hole. Then, these 5 points will be averaged and taken as area average adiabatic wall temperature. Next hole hot gas temperature will be taken as mixing adiabatic wall temperature coming from previous hole at related x/s location.





TUSAŞ MOTOR SANAYİİ A.Ş.
TUSAŞ ENGINE INDUSTRIES, INC.

THANK YOU

TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Malzeme Teknik Eğitim

10.01.2023

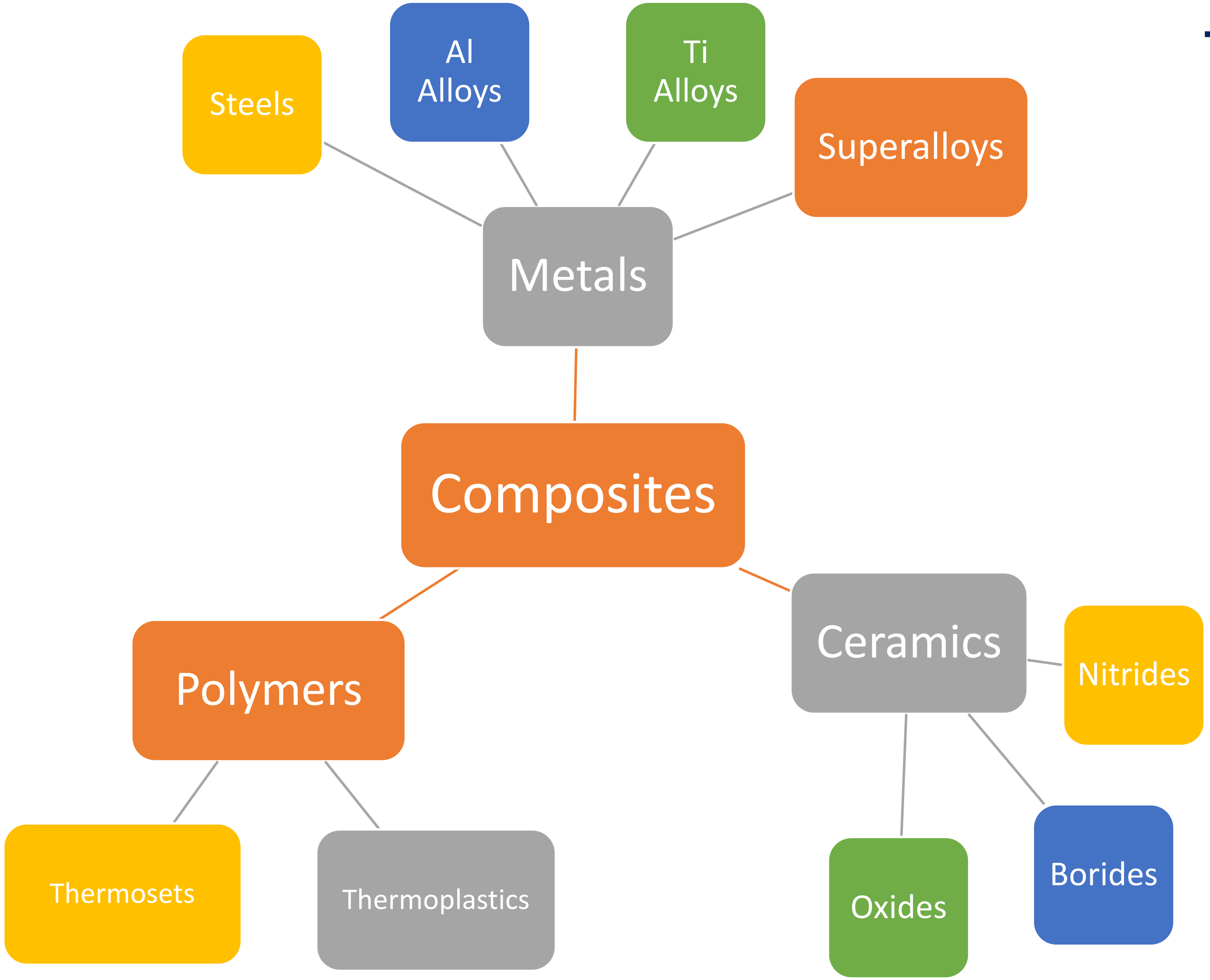
INTRODUCTION

- Materials
- Gas Turbine Engine Materials
- Piston Engine Materials

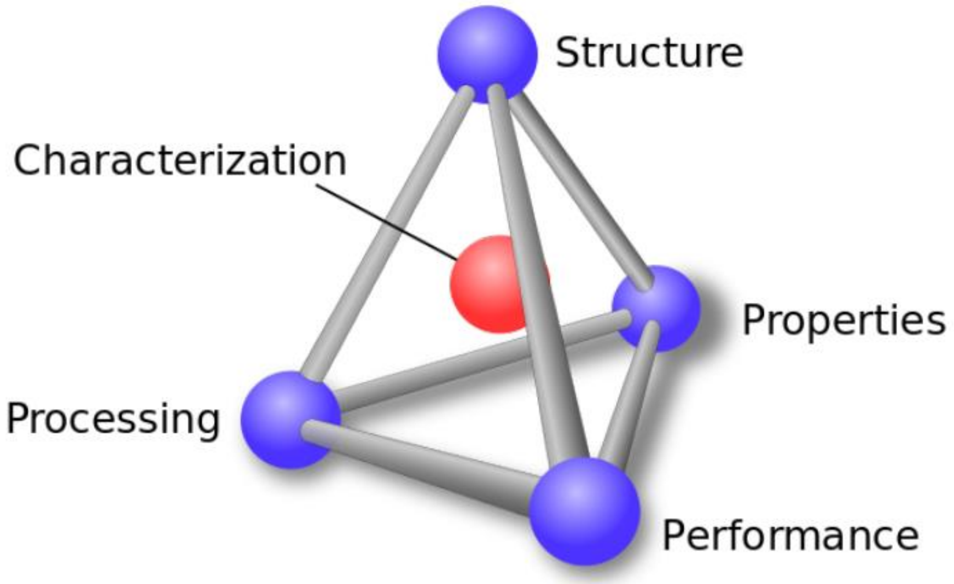
METALS and SPECIAL PROCESSES

- Aluminum and Aluminum Alloys
- Titanium and Titanium Alloys
- Stainless Steel
- Superalloys
- Special Processes
- Testing

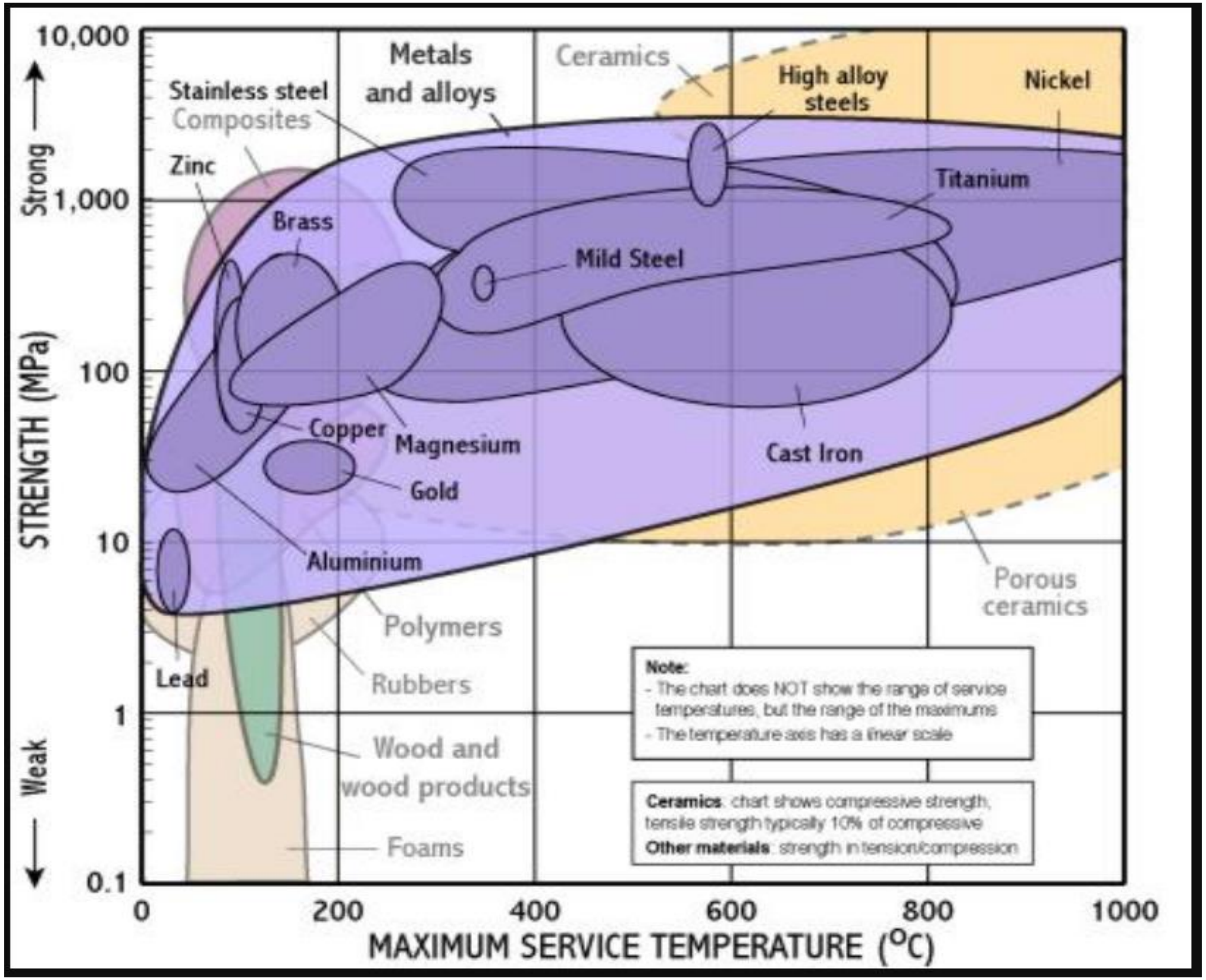
MATERIALS



- Composites
  - Metals
    - Steels
    - Al Alloys
    - Ti Alloys
    - Superalloys
  - Polymers
    - Thermosets
    - Thermoplastics
  - Ceramics
    - Nitrides
    - Borides
    - Oxides



MATERIALS



Note:
- The chart does NOT show the range of service temperatures, but the range of the maximums
- The temperature axis has a linear scale

Ceramics: chart shows compressive strength, tensile strength typically 10% of compressive
Other materials: strength in tension/compression

Ashby, M. F., *Materials selection in mechanical design,* 1999.

Maximum service temperature and **strength** of different materials groups

GAS TURBINE ENGINE MATERIALS

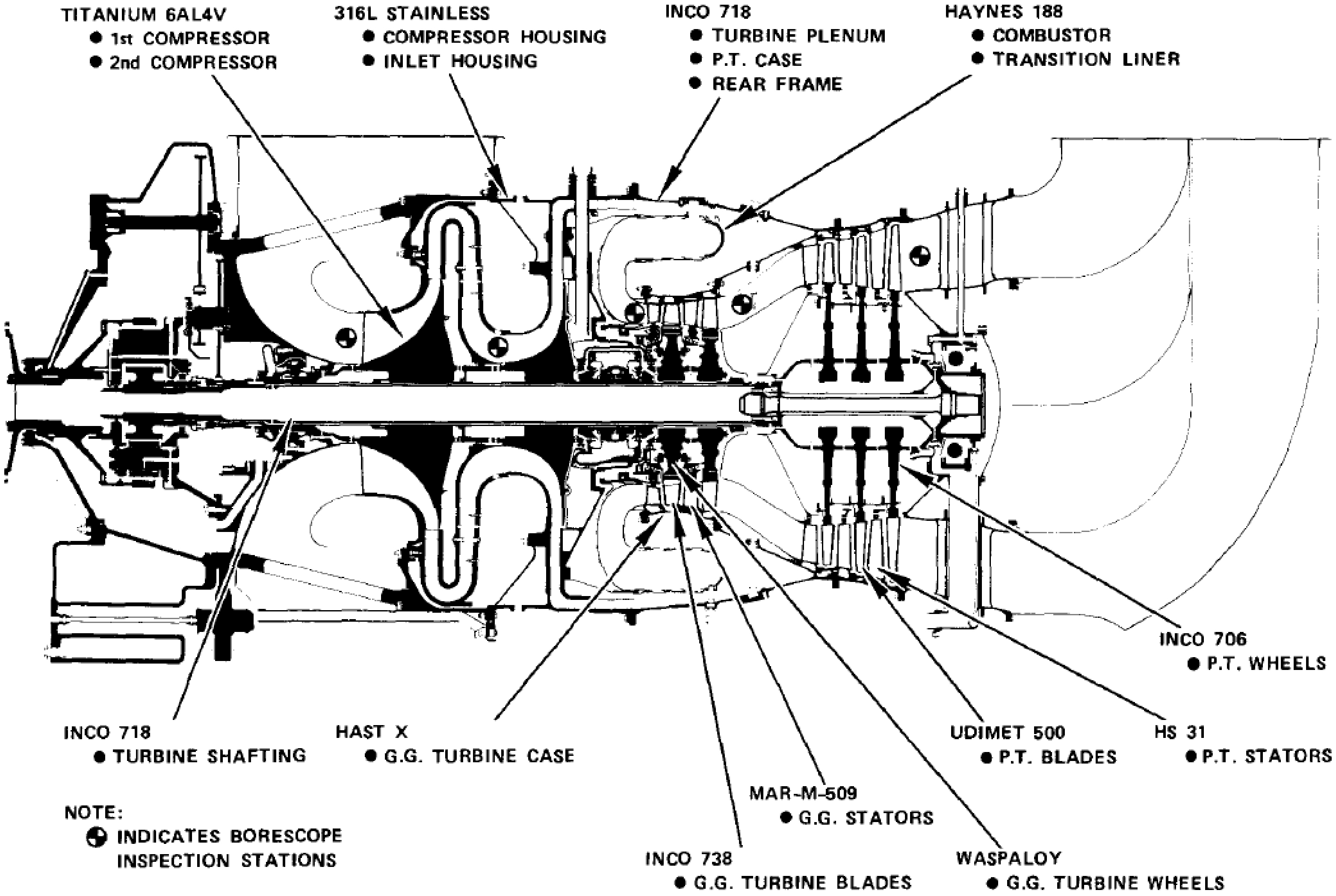
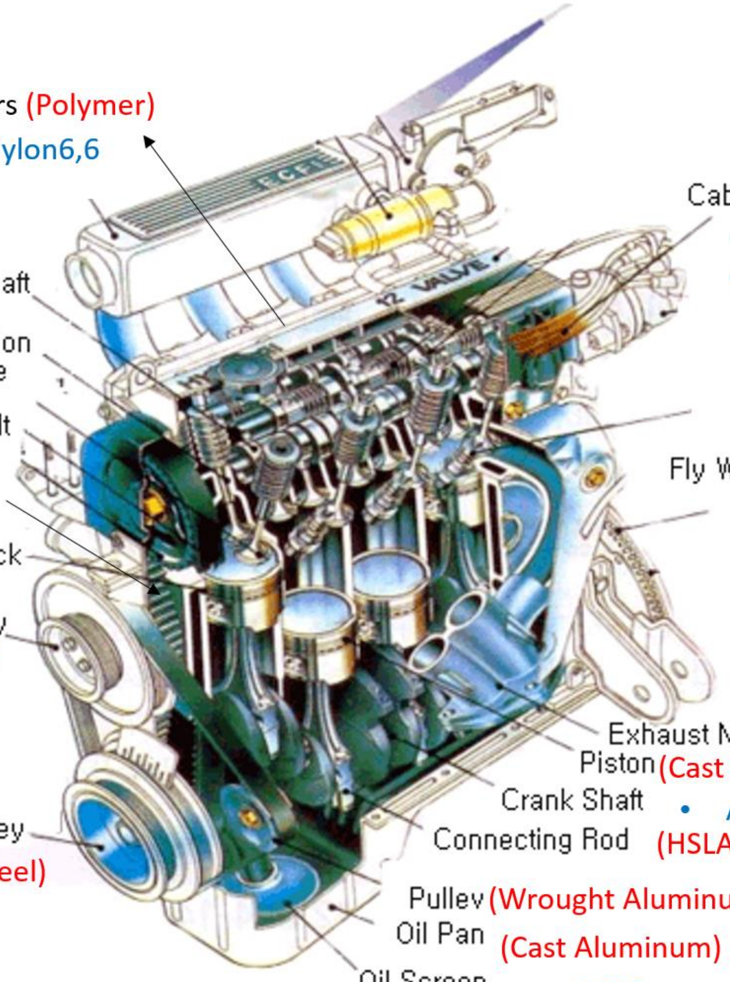


Fig. 2 GTPF990 configuration and materials

PISTON ENGINE MATERIALS



Covers (Polymer)
- Nylon6,6

Cable (Polymer insulation)
- Polyethylene
- Polypropylene

(HSLA steels) Cam Shaft

(High temperature resistant Stainless steels) Inhalation Valve
- X53CrMnNiN21-9

(Polymer composite) Timing Belt
- Fiber reinforced rubber

(HSLA steels) Gears

(Cast Aluminum) Cyliner Block
- A356 and A357

Water Pump Pulley (Wrought Aluminum)
- 7075
- 6061

Crank Shaft Pulley (Plain carbon steel)
- 1040
- 1020

Fly Wheel (HSLA steels)
- 4340
- 4140
- 8640

Exhaust Manifold (High temperature resistant Stainless steels)
- 310 SS
- 321 SS

Piston (Cast Aluminum)
- AlSi18CuMgNi-Hyper eutectic

Crank Shaft

Connecting Rod (HSLA steels)

Pulley (Wrought Aluminum)

Oil Pan (Cast Aluminum)
- A356
- AlSi7Mg0,3-Hypo eutectic

Oil Screen

ALUMINIUM AND ALUMINIUM ALLOYS

- The second most plentiful metallic element on earth has a density of only 2.7 g/cm3

- Aluminum surfaces can be highly reflective. Radiant energy, visible light, radiant heat, and electromagnetic waves are efficiently reflected, while anodized and dark anodized surfaces can be reflective or absorbent. The reflectance of polished aluminum, over a broad range of wave lengths, leads to its selection for a variety of decorative and functional uses.

- Typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity.

- Nonpyrophoric, which is important in applications involving inflammable or explosive-materials handling or exposure. Aluminum is also nontoxic and is routinely used in containers for foods and beverages.

- Some aluminum alloys exceed structural steel in strength

ALUMINIUM AND ALUMINIUM ALLOYS

Wrought alloys

- 1xxx Controlled unalloyed (**pure**) compositions
- 2xxx **Copper** principal alloying element
- 3xxx **Manganese** principal alloying element
- 4xxx **Silicon** principal alloying element
- 5xxx **Magnesium** principal alloying element
- 6xxx **Magnesium** and **silicon**
- 7xxx **Zinc** principal alloying element
- 8xxx Alloys including **tin and some lithium** compositions characterizing miscellaneous compositions
- 9xxx Reserved for future use

Cast alloys

- 1xx.x Controlled unalloyed (**pure**) compositions
- 2xx.x **Copper** principal alloying element
- 3xx.x **Silicon** principal alloying element but **Cu** and **Mg** are specified
- 4xx.x **Silicon** principal alloying element
- 5xx.x **Magnesium** principal alloying element
- 7xx.x **Zinc** principal alloying element
- 8xx.x **Tin** principal alloying element

ALUMINIUM AND ALUMINIUM ALLOYS

T-tempers: Alloys that are strengthened substantially by precipitation hardening; alloys
that receive solution heat treatment and subsequently precipitation heat treatment (aging).

Major tempers among the 9 different tempers:

T1:Quenching after high temperature forming operation + room temperature storage for a stable structure / natural ageing

T2: Quenching after high temperature forming operation + cold deformation + room temperature storage for a stable structure / natural ageing

T3: Solution heat treatment + cold deformation + storage at room temperature for stable structure / natural ageing

T4:Solution heat treatment + storage at room temperature for stable structure /natural ageing

T5:Quenching from the high temperature forming operation + artificial ageing

T6: Solution heat treatment + artificial ageing

T7:Solution heat treatment + artificial ageing beyond the peak hardness (to increase ductility at the expense of strength!)

T8:Solution heat treatment + cold forming + artificial ageing

T9:Solution heat treatment + artificial ageing + cold forming

Common Alloys used in aeroengines

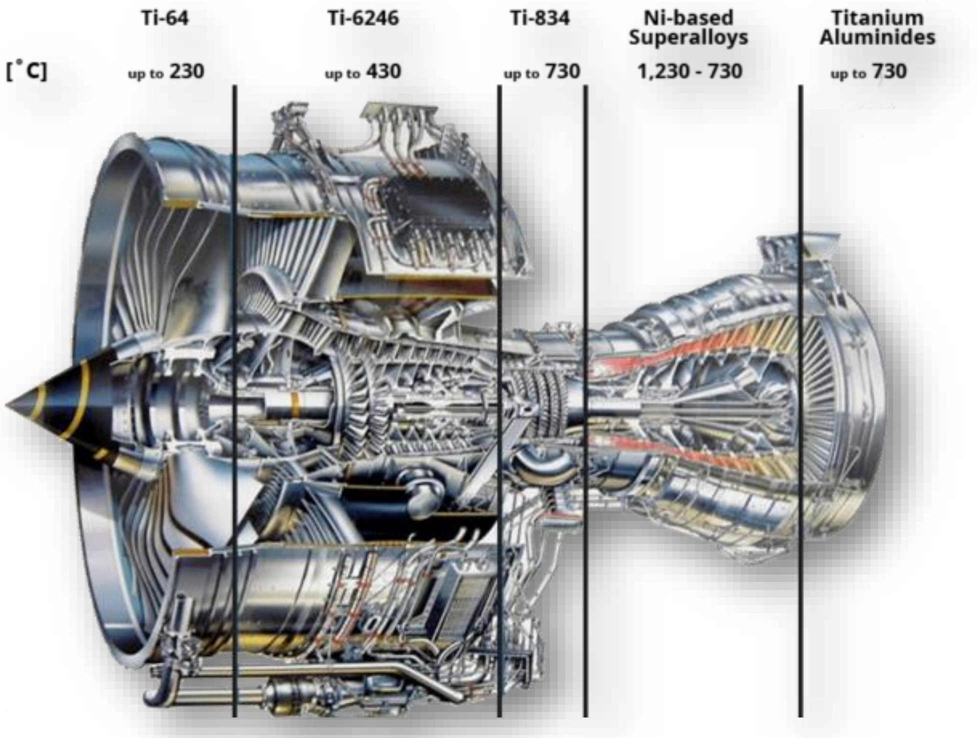
- A357 cast
- 2024 wrought
- 2124 wrought
- 6061 wrought
- 7075 wrought
- AlSi10Mg- cast, additive

TITANIUM AND TITANIUM ALLOYS

Titanium alloys are important engineering materials.
Due to;

- High tensile strength to density ratio
- High corrosion resistance
- Has ability to withstand moderately high temperatures without creeping.
- Can be manufactured in variety forms (forge, bar, sheet etc.).

- Titanium alloys have **lower density** and exhibit high strength to density ratio which makes titanium parts much more lighter than other materials.
- Weight is an important criteria in aircraft design since it is **directly related with fuel consumption.**



Cross section through a Trent 900 aero engine, Rolls Royce

TITANIUM AND TITANIUM ALLOYS

- ✓ Higher density
- ✓ Increasing heat treatment response
- ✓ Increasing strain rate sensitivity
- ✓ Higher short-time strength
- ✓ Improved fabricability

Alpha Alloys	**Near–Alpha Alloys**	**Alpha–Beta Alloys**	**Near–Beta Alloys**	**Beta Alloys**
Pure Ti Ti-5Al-2.5Sn	Ti-5Al-6Sn-2Zr-1Mo-0.2Si Ti-6Al-2Sn-4Zr-2Mo Ti-8Al-1Mo-1V (Ti-811) Ti-2Al-11Sn-5Zr-1Mo-0.2Si (IMI-679) Ti-3Al-6Sn-4Zr-0.5Mo-0.5Si (Hylite-65) Ti-6Al-5Zr-0.5Mo-0.25Si (IMI-685) Ti-6Al-2.75Sn-4Zr-0.4Mo-0.45Si (Ti-1100)	Ti-6Al-4V Ti-6Al-6V-2Sn Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17) Ti-4Al-2Sn-4Mo-0.5Si (IMI-550) Ti-5Al-5Sn-2Zr-2Mo-0.2Si (Ti-5522S) Ti-5Al-5Sn-2Zr-4Mo-0.1Si (Ti-5524S)	Ti-8Mn	Ti8Mo-8V-2Fe-3Al Ti11.5Mo-6Zr-4.5Sn Ti-13V-11Cr-3Al Ti-15Mo-3Al-2.75Nb-0.25Si(Beta-21S) Ti-15V-3Al-3Cr-3Sn

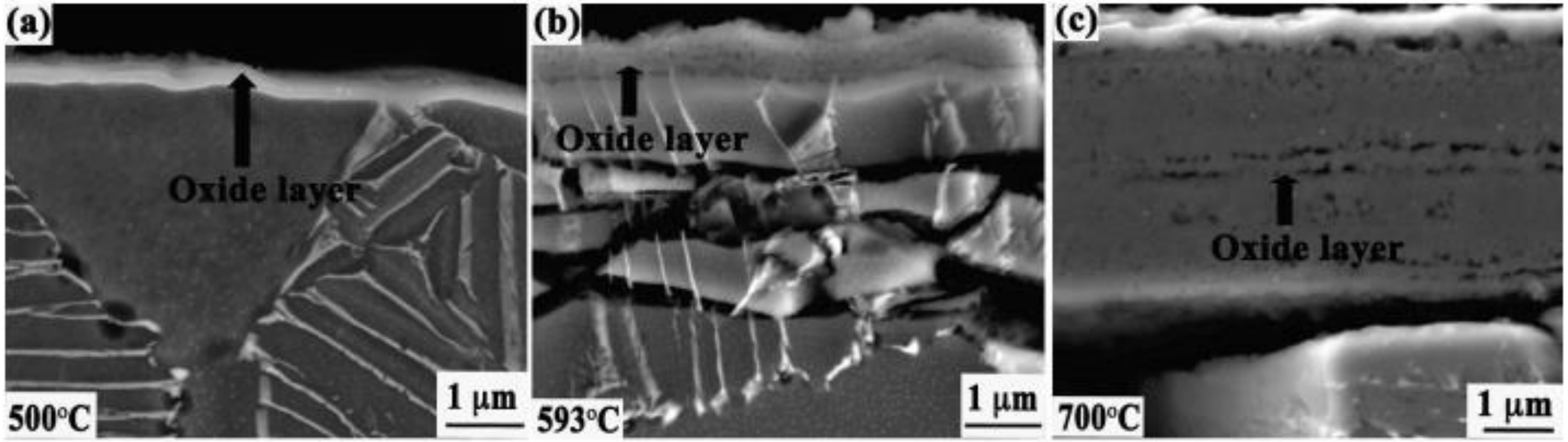
- ✓ Improved weldability
- ✓ Higher creep strength

- Titanium exists in two crystallographic forms.
  - At room temperature, unalloyed (commercially pure) titanium has a hexagonal close-packed (hcp) crystal structure referred to as alpha phase.
  - At 883 °C , this transforms to a body-centered cubic (bcc) structure known as beta (ß) phase.
  - The manipulation of these crystallographic variations through alloying additions and thermomechanical processing is the basis for the development of a wide range of alloys and properties.
  - These phases also provide a convenient way to categorize titanium mill products. Based on the phases present, titanium alloys can be classified as either . α alloys, ßalloys, or α + ß alloys.

TITANIUM AND TITANIUM ALLOYS

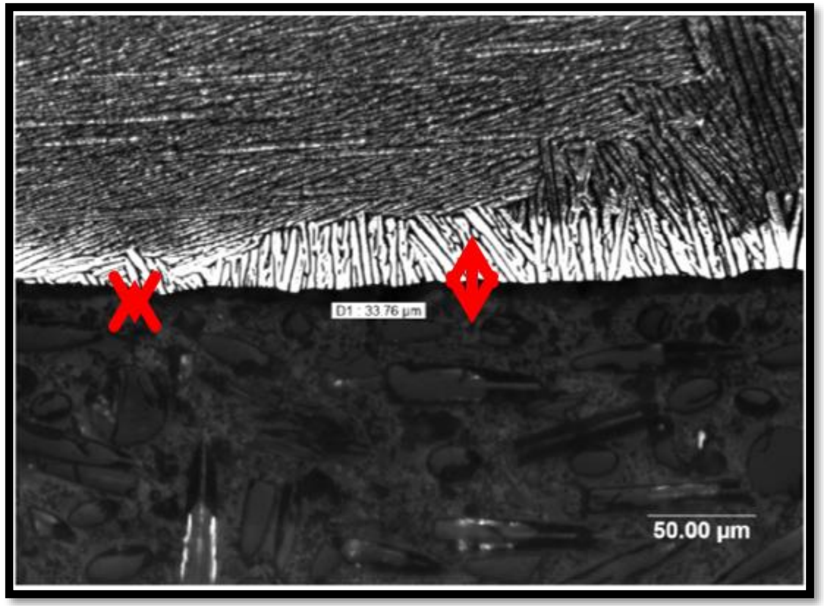
Titanium has **high affinity to react with oxygen** when exposed to oxidizing environments. The reaction between titanium and oxygen at room temperature results in the **formation of a thin and passive TiO_2 layer** that ***provides protection of the metal surface from further oxidation and corrosion*** in various corrosive environments.

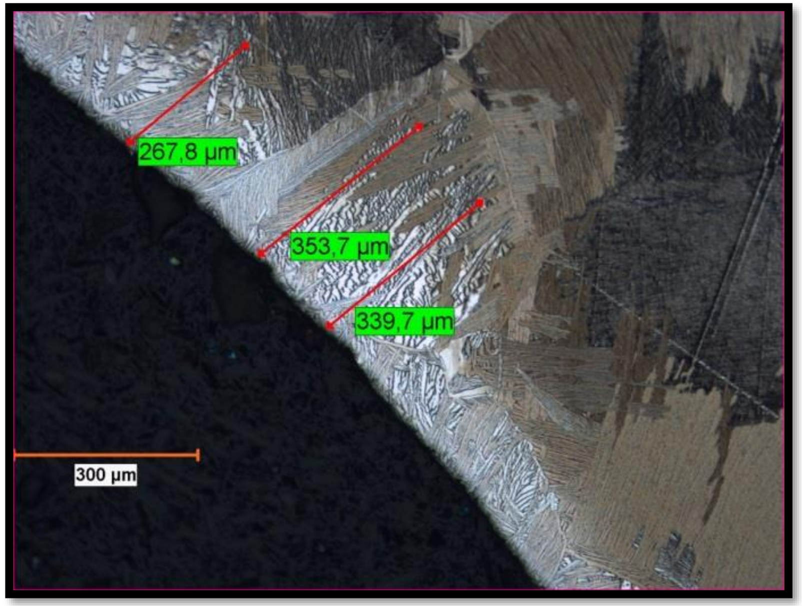
- **However,** at elevated temperatures the TiO_2 layer loses its protectiveness and allows oxygen to be dissolved into the titanium bulk metal. This is the main factor that limits the service temperature of titanium alloys.



SEM micrographs showing the oxide scale 500 hours exposure time (a) 500C, (b) 593 C,, (c) 700C

TITANIUM AND TITANIUM ALLOYS-ALPHA CASE

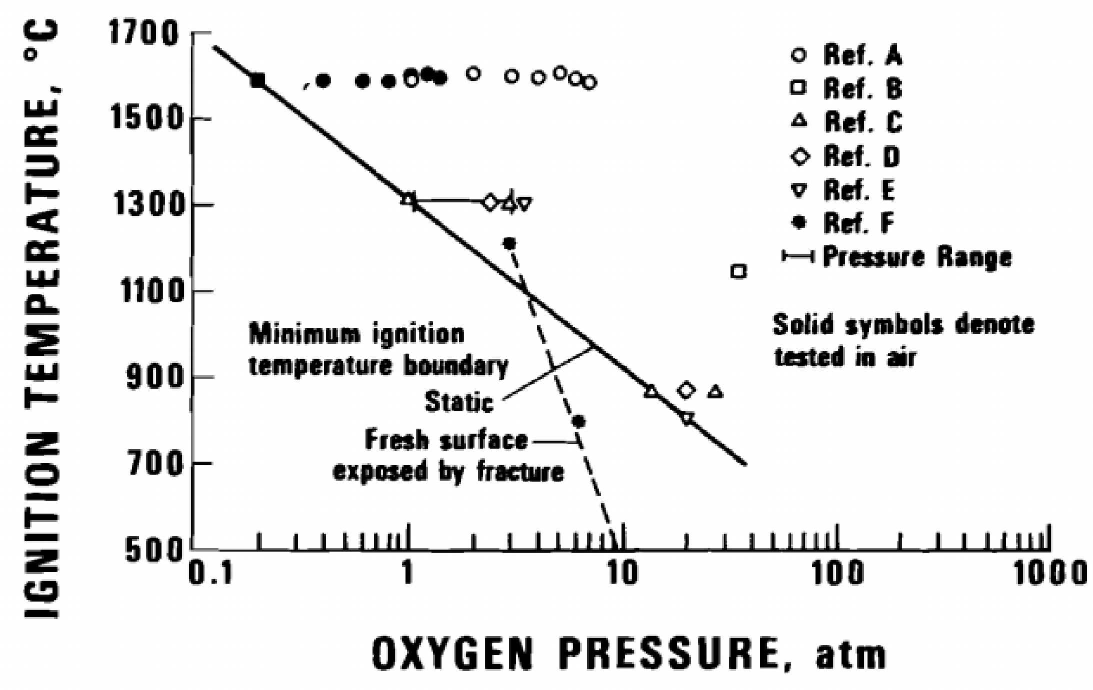




Beside formation of TiO2 scale on the surface in oxidizing environment, an oxygen-rich layer beneath the scale will form, commonly referred to as alpha-case (α-case). Alpha-case is a continuous, hard, and brittle layer with higher oxygen content . It forms because of higher solid solubility of oxygen in α-titanium and higher affinity of titanium to absorb oxygen, which instantaneously reacts and stabilize the α phase. This brittle alpha-case degrades the mechanical properties such as tensile ductility and fatigue strength. Therefore it is necessary to remove any alpha-case formed on parts manufactured from titanium alloys if they are subjected to high loads and/or dynamic loading conditions.

TITANIUM FIRE

- With the increase in titanium usage in aero-engines, titanium fire risk is raised. Titanium is a flammable metal which can be self ignited under high temperature & pressure. It can also be ignited by rubbing or get hit by an object (like blade fragment etc.) which then provides a bare, oxide-free surface necessary for ignition (metal-metal contact).



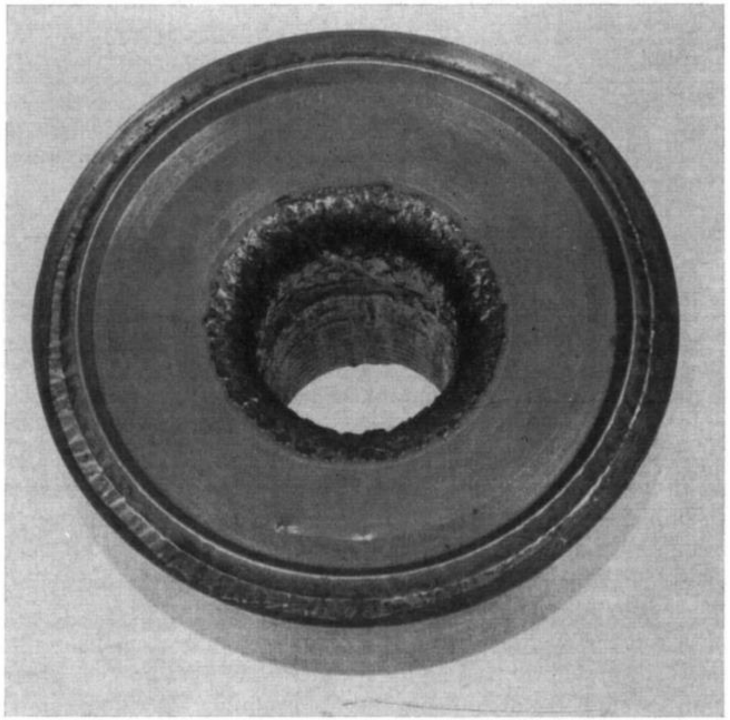


Fig. 9. Rupture disk after reaction.

J. Less-Common Metals, 3 (1961)

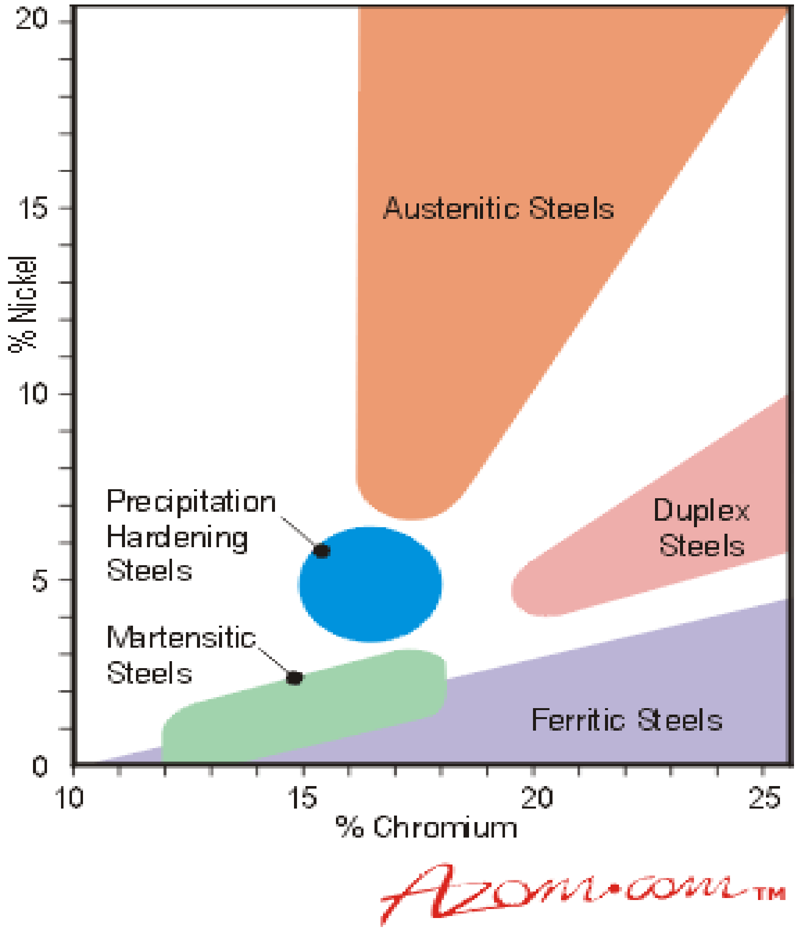
BLUE ETCH ANODIZING

Blue etch anodizing (BEA) is a specialized, highly sensitive non-destructive testing technique for detecting surface discontinuities such as laps, cracks, material segregation, heat-treating imperfections and abnormalities caused by machining.

- Blue etch anodizing is only applicable to the detection of discontinuities in titanium materials such as those used in the manufacture of critical rotating parts for the Aerospace and Power Generation industries.
- Only for wrought Ti alloys

STAINLESS STEEL

Stainless Steels → Fe
≥ %10,5 Cr
≤ %1,2 C



Stainless Steel can be classified into 4 main types depends to Cr and/or Ni ratio;

Ferritic

- %10.5 – 18 Cr
- Moderate corrosion resistance
- Poor fabrication properties

Austenitic

- Min %16 Cr, %6 Ni
- FCC structure
- Can be modified to optain corrosion resistance, high temp. strength by additional elements (Ti, Al, Mo etc)
- Easy to Weld
- Easy to Machine

Martensitic

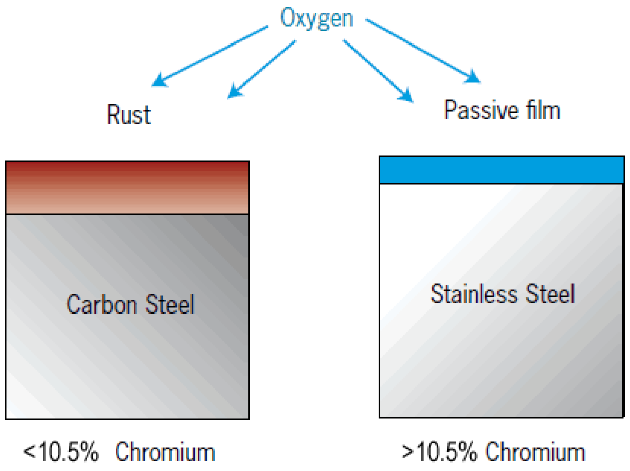
- Cr is the major alloying element
- Cr can be decreased by increasing C content
- Brittle

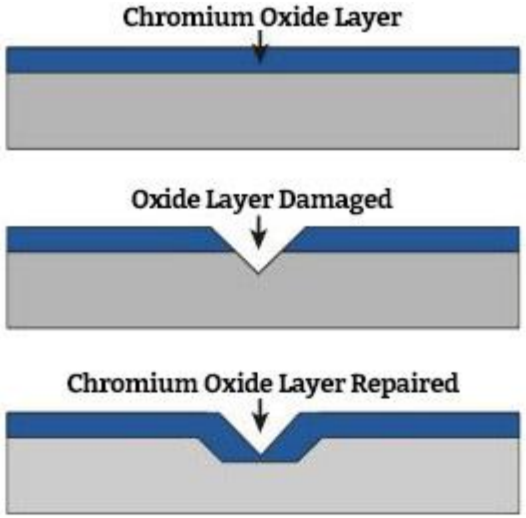
Duplex

- Mixture of Austenite and ferrite
- Used between -50 to 300 ˚C
- Superior toughness

STAINLESS STEEL-CORROSION RESISTANCE

- The unique corrosion resistance of stainless steels is attributed to the existence of a thin, adherent, inactive passive film that covers the surface.
- This film can conveniently be thought of as **chromium oxide**, but it also contains small amounts of the other elements in the alloy.
- It is extremely durable and reforms spontaneously. Because of this protective film, stainless steels do not corrode as carbon or low alloy steels or cast iron do.
- While factors such as chemical environment, pH, temperature, equipment design, fabrication methods, surface finish, contamination, and maintenance procedures can affect the corrosion of stainless steels, they usually cause only some form of localized corrosion.





STAINLESS STEEL-SELECTION

There are a large number of standard types that differ from one another in composition, corrosion resistance, physical properties, and mechanical properties; selection of the optimum type for a specific application is the key to satisfactory performance at minimum total cost.

- Corrosion resistance
- Resistance to oxidation and sulfidation
- Strength and ductility at ambient and service temperatures
- Suitability for intended fabrication techniques
- Suitability for intended cleaning procedures
- Stability of properties in service
- Toughness
- Resistance to abrasion and erosion
- Resistance to galling and seizing
- Surface finish and/or reflectivity
- Magnetic properties
- Thermal conductivity
- Electrical resistivity
- Sharpness (retention of cutting edge)
- Rigidity

Commonly used alloys in aeroengines

- AISI 304
- AISI 321
- AISI 316
- 17-4PH
- 13-8 PH

PRECIPITATION-HARDENING STAINLESS STEELS

- The first PH stainless steels were developed in the 1940’s by Smith et al. and many others have been developed since then.

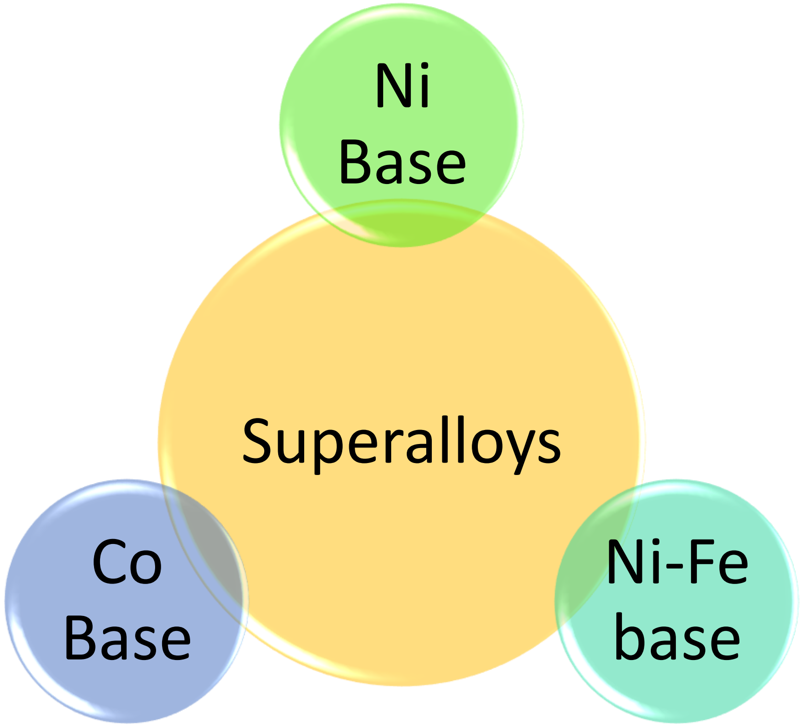
- Due to the high strength, corrosion resistance and relatively good ductility of these alloys they have been used for applications in the chemical, aerospace, naval and nuclear industries

- Precipitation-hardening stainless steels may be either austenitic or martensitic in the annealed condition. Those that are austenitic in the annealed condition are frequently transformable to martensite through conditioning heat treatments, sometimes with a subzero treatment.

- These stainless steels attain high strength by precipitation hardening of the martensitic structure.

- Generally heat treated to final properties by the fabricator.

SUPERALLOYS



Ni Base

Superalloys

Co Base

Ni-Fe base

Why are they called **superalloys**?

SUPERALLOYS

Superalloys are used at temperatures of 540 ˚C and above

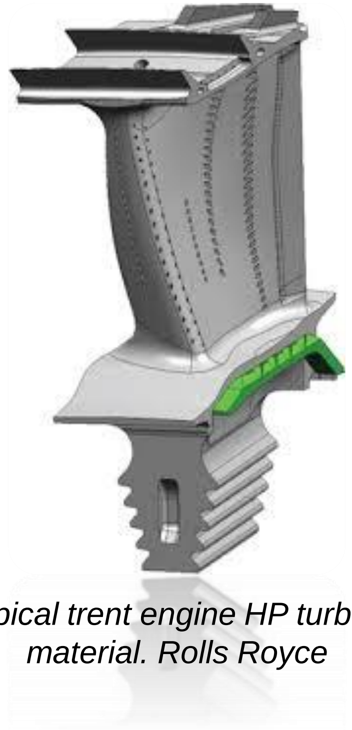
Used in load bearing applications at temperatures in excess of *80% of their incipient melting temperature*

- High strength at a temperature
- Resistance to enviromental attack
- Excellent creep resistance, stress-rupture strength, toughness and stability
- Resistance to thermal fatigue and corrosion

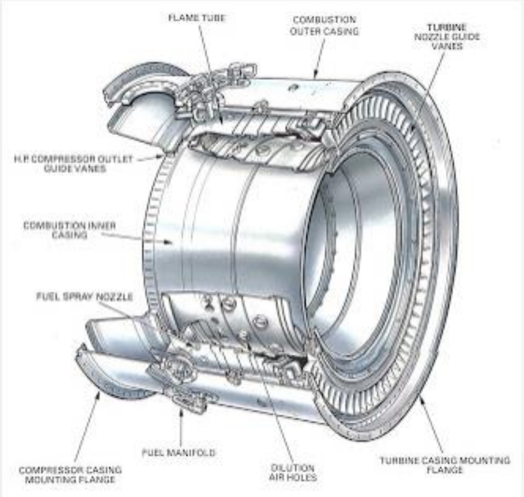
When significant resistance to loading under static, fatigue and creep conditions is required, the nickel-base superalloys have emerged as the materials of choice for high temperature applications. This is particularly true when operating temperatures are beyond about 800 ˚C.

SUPERALLOYS

- ➢ Superalloys constitute a large fraction of the materials of construction in turbine engines because of their unique combination of physical and mechanical properties.
- ➢ In aircraft engines, it is typical to consider density-normalized properties; thus alloy densities, which are typically in the range of 7.7–9.0 g/cm3, are of specific interest.
- ➢ Optimization of the relevant set of mechanical properties is of paramount importance and is dependent on a high level of control and understanding of the processes summarized, because mechanical properties are a strong function of microstructure.



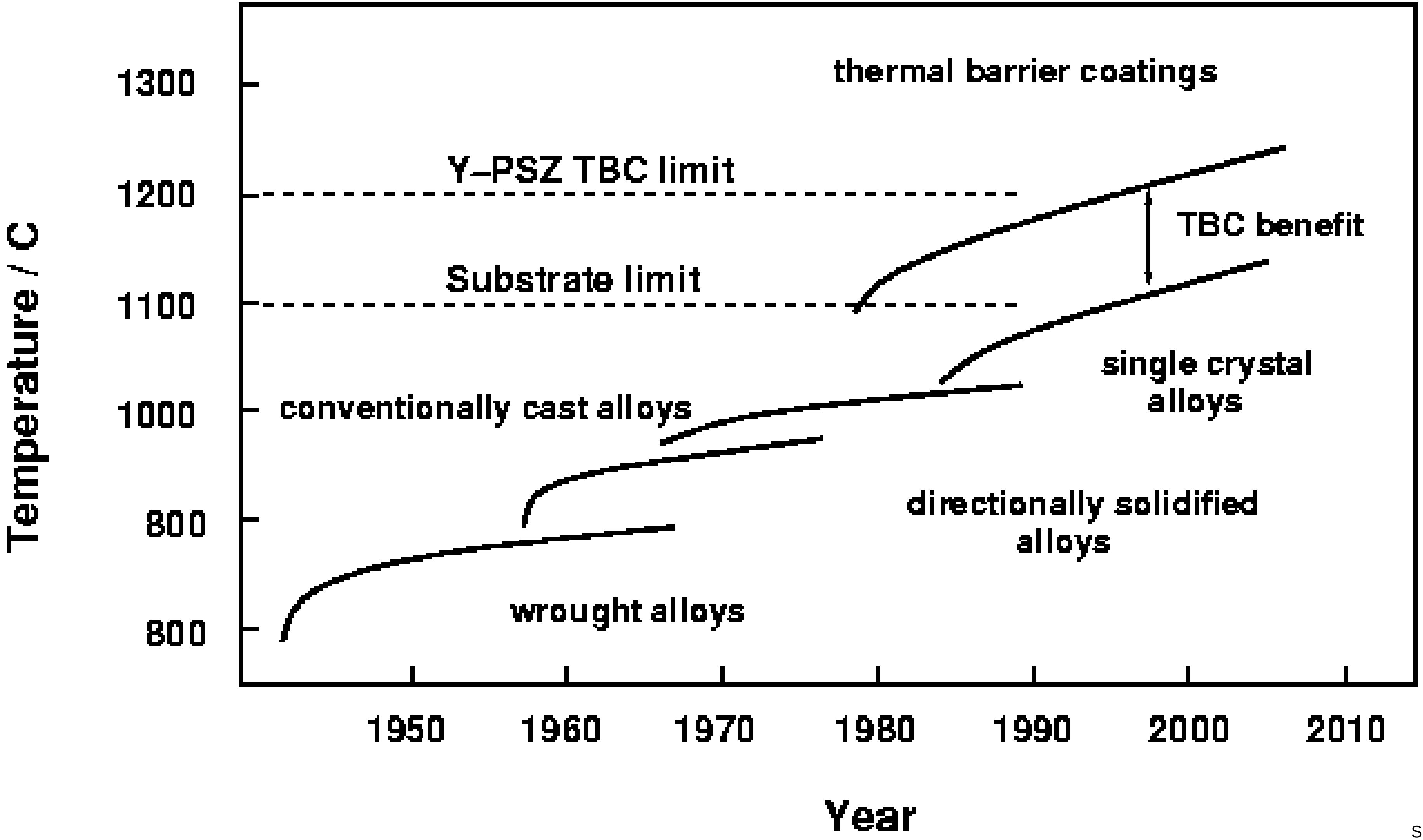
Typical trent engine HP turbine material. Rolls Royce



http://aeromodelbasic.blogspot.com/2012/01/combustion-chamber-performance.html

SUPERALLOYS

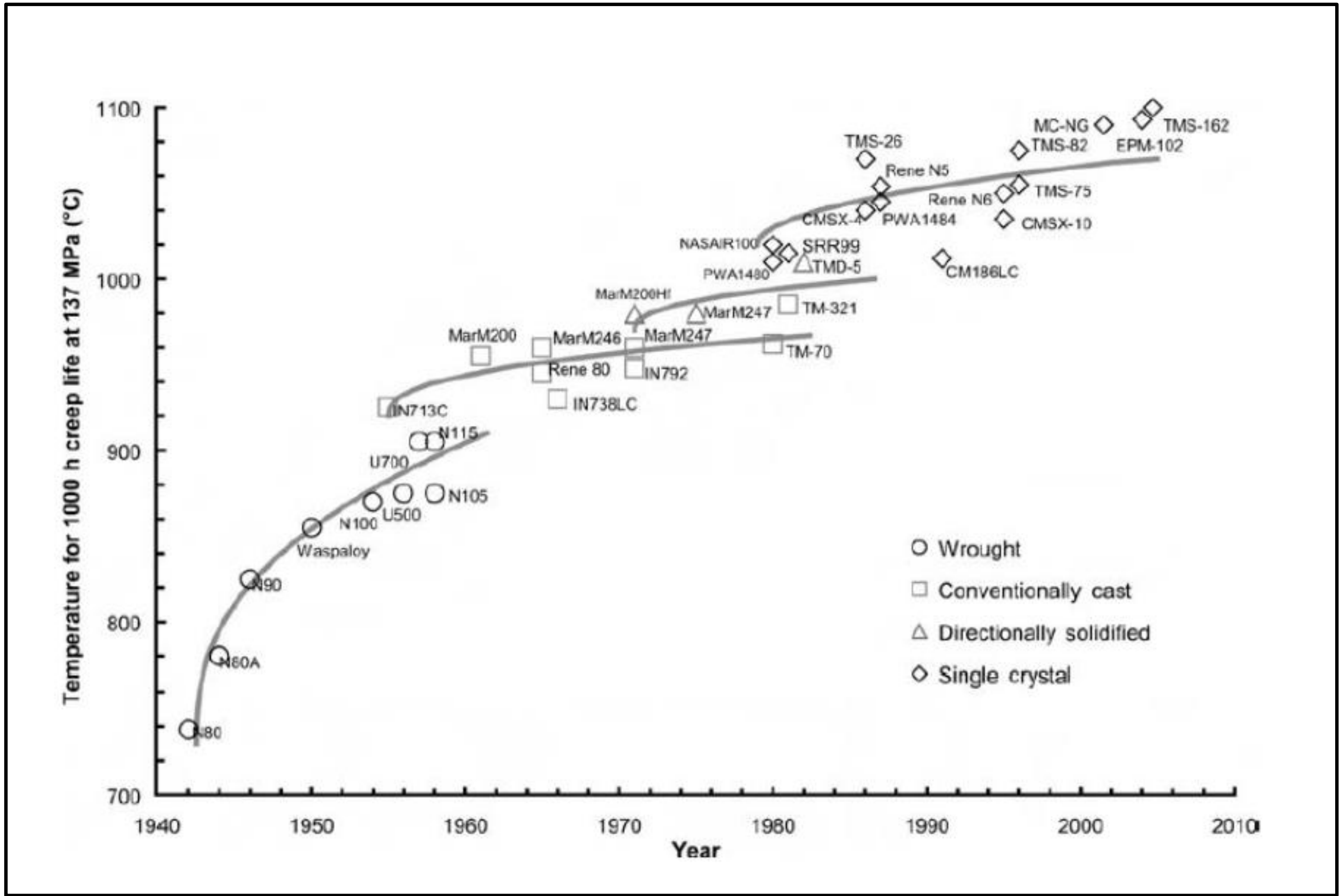
Increase in **operational temperature** of turbine components



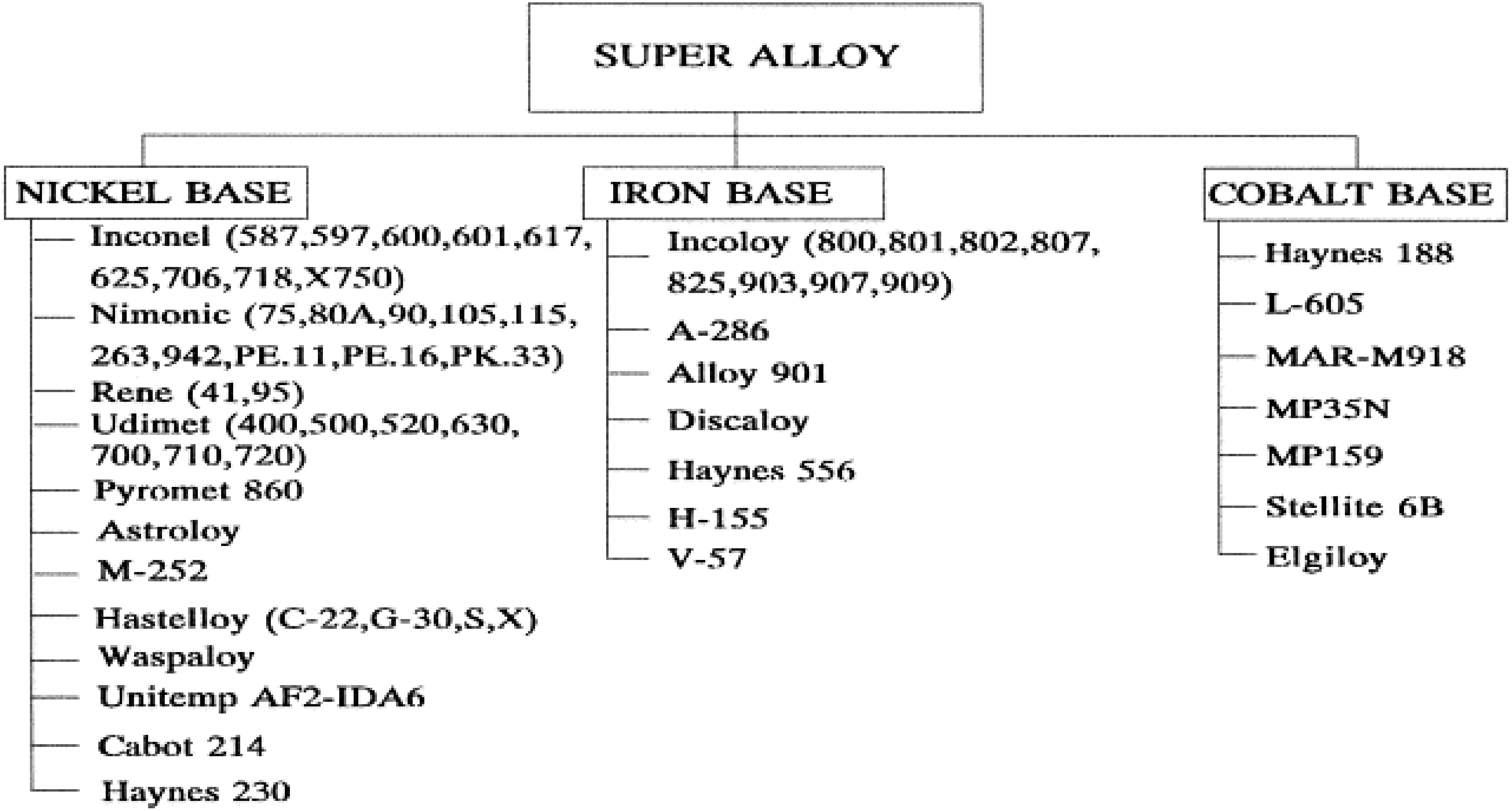
Schulz *et al*, Aero. Sci. Techn.**7**:2003, p73-80

SUPERALLOYS

Creep life change of superalloys over the years



SUPERALLOYS

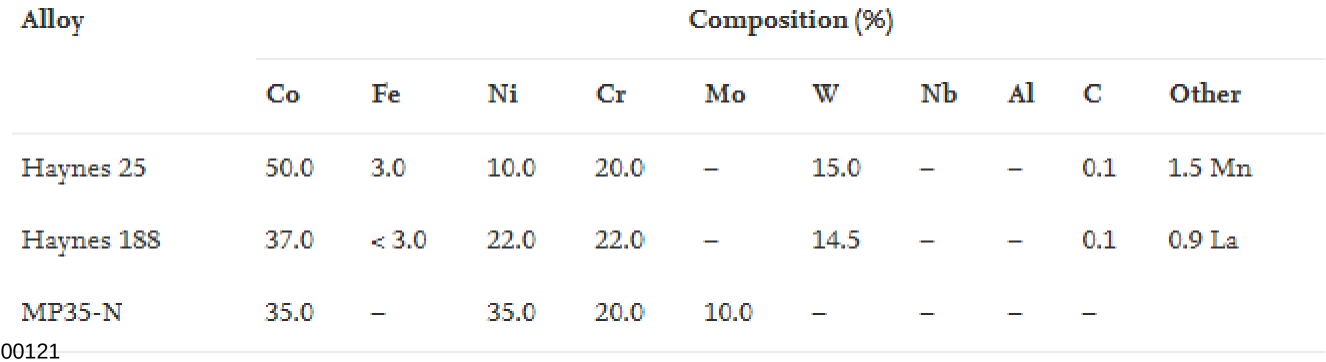


- SUPER ALLOY
  - NICKEL BASE
    - Inconel (587,597,600,601,617, 625,706,718,X750)
    - Nimonic (75,80A,90,105,115, 263,942,PE.11,PE.16,PK.33)
    - Rene (41,95)
    - Udimet (400,500,520,630, 700,710,720)
    - Pyromet 860
    - Astroloy
    - M-252
    - Hastelloy (C-22,G-30,S,X)
    - Waspaloy
    - Unitemp AF2-IDA6
    - Cabot 214
    - Haynes 230
  - IRON BASE
    - Incoloy (800,801,802,807, 825,903,907,909)
    - A-286
    - Alloy 901
    - Discaloy
    - Haynes 556
    - H-155
    - V-57
  - COBALT BASE
    - Haynes 188
    - L-605
    - MAR-M918
    - MP35N
    - MP159
    - Stellite 6B
    - Elgiloy

https://www.sciencedirect.com/science/article/pii/S0924013697004299

COBALT BASED SUPERALLOYS

- The cobalt-base superalloys have their origins in the Stellite® alloys
- Although in terms of properties the hardened nickel-based alloys ("Y" alloy) have taken the majority share of the superalloy market, cast and wrought cobalt alloys continue to be used because of the following characteristics:
    - Higher melting points than nickel (or iron) alloys
    - Superior hot corrosion resistance to gas turbine atmospheres
    - Superior thermal fatigue resistance and weldability over nickel superalloys
- Compared to nickel superalloys, the stress rupture curve for cobalt superalloys is flatter and shows lower strength up to 930°C. The greater stability of the carbides, which provide strengthening of cobalt superalloys, is then exhibited. This factor is the primary reason cobalt superalloys are used in the lower stress, higher temperature stationary vanes for gas turbines.
- Wrought cobalt-base alloys, unlike other superalloys, are not strengthened by a coherent, ordered precipitate. Rather, they are characterized by a solid solution strengthened austenitic (fcc) matrix in which a small quantity of carbides is distributed
- Due to high Cr content, oxidation resistance at high temperatures are better
- display superior hot corrosion resistance at high temperatures, probably a consequence of the considerably higher chromium contents that are characteristic of these alloys.
- Cobalt-base alloys generally exhibit better weldability and thermal-fatigue resistance than do nickel-base alloys.

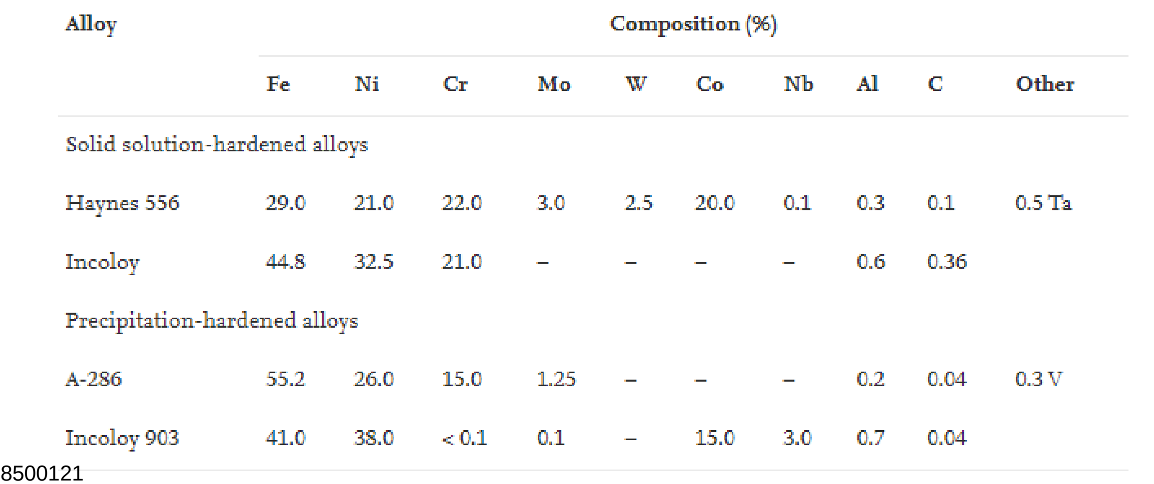


Alloy	Composition (%)									
	Co	Fe	Ni	Cr	Mo	W	Nb	Al	C	Other
Haynes 25	50.0	3.0	10.0	20.0	–	15.0	–	–	0.1	1.5 Mn
Haynes 188	37.0	< 3.0	22.0	22.0	–	14.5	–	–	0.1	0.9 La
MP35-N	35.0	–	35.0	20.0	10.0	–	–	–	–	

https://www.sciencedirect.com/science/article/pii/B9781855739468500121

IRON-NICKEL BASED SUPERALLOYS

- Fe is added to replace some Ni as it has lower cost
- Ni-Fe superalloys contain 25-45 %Ni and 15-60 %Fe. The austenitic matrix is based on nickel and iron, with at least 25% Ni needed to stabilize the fcc phase. Other alloying elements, such as chromium, partition primarily to the austenite for solid-solution hardening.
- Microstructure consists of austenitic fcc matrix and can be strengthened by solid solution strenthening (Mo, Cr) and precipitation hardening (Ti, Nb, Al) by forming intermetallic phases
- Good resistance to creep, oxidation, corrosion and wear
- Oxidation resistance increases with Cr content
- Alloys that are strengthened by ordered fcc γ', such as V-57 and A-286, and contain 25 to 35 wt% Ni, represent one subgroup. The γ' phase is titanium-rich in these alloys, and care must be taken to avoid an excessively high titanium-to aluminum ratio, resulting in the replacement of fcc γ' by hexagonal closepacked (hcp) γ (Ni3Ti), a less effective strengthener.
- A second iron-rich subgroup, of which Inconel X750 and Incoloy 901 are examples, contains at least 40% Ni, as well as higher levels of solid-solution strengthening and precipitate-forming elements.



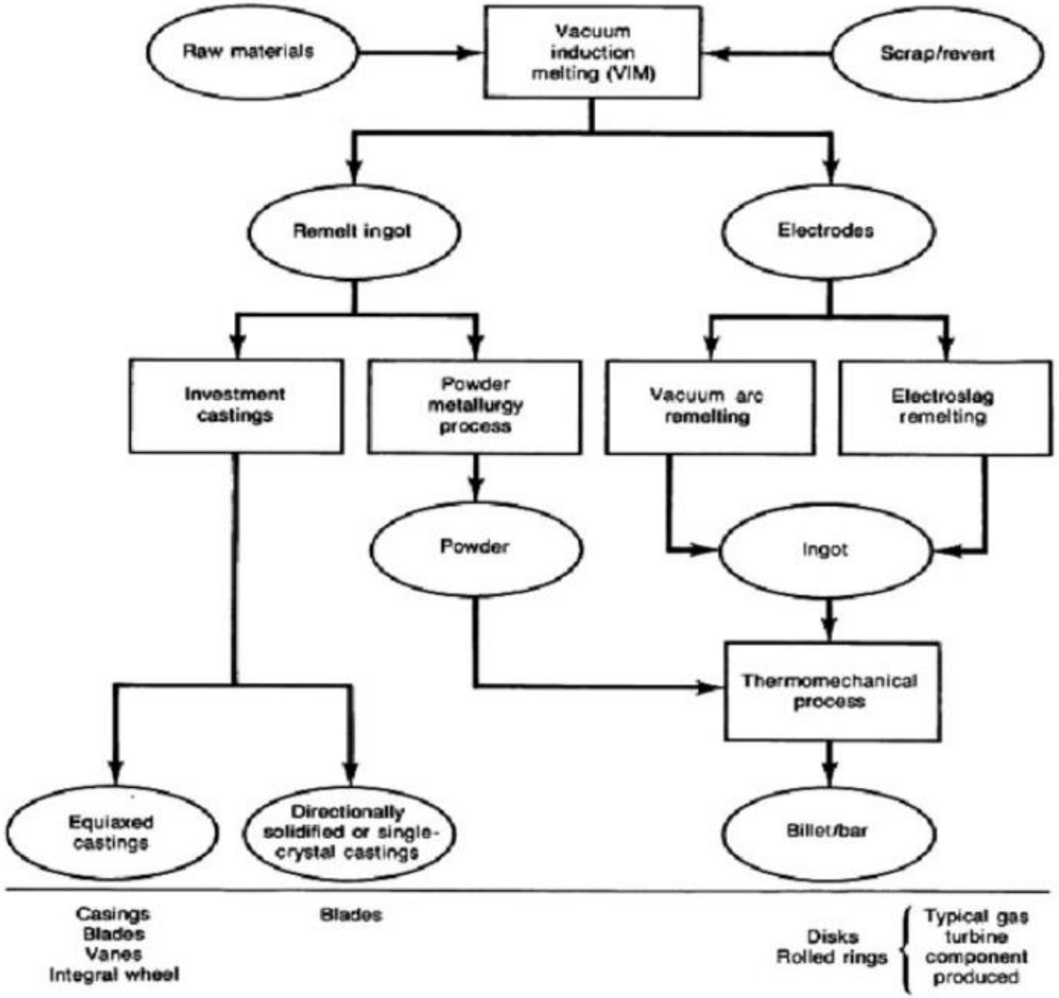
Alloy	Composition (%)									
	Fe	Ni	Cr	Mo	W	Co	Nb	Al	C	Other
Solid solution-hardened alloys										
Haynes 556	29.0	21.0	22.0	3.0	2.5	20.0	0.1	0.3	0.1	0.5 Ta
Incoloy	44.8	32.5	21.0	–	–	–	–	0.6	0.36	
Precipitation-hardened alloys										
A-286	55.2	26.0	15.0	1.25	–	–	–	0.2	0.04	0.3 V
Incoloy 903	41.0	38.0	< 0.1	0.1	–	15.0	3.0	0.7	0.04	

https://www.sciencedirect.com/science/article/pii/B9781855739468500121

SUPERALLOYS-PROCESSING

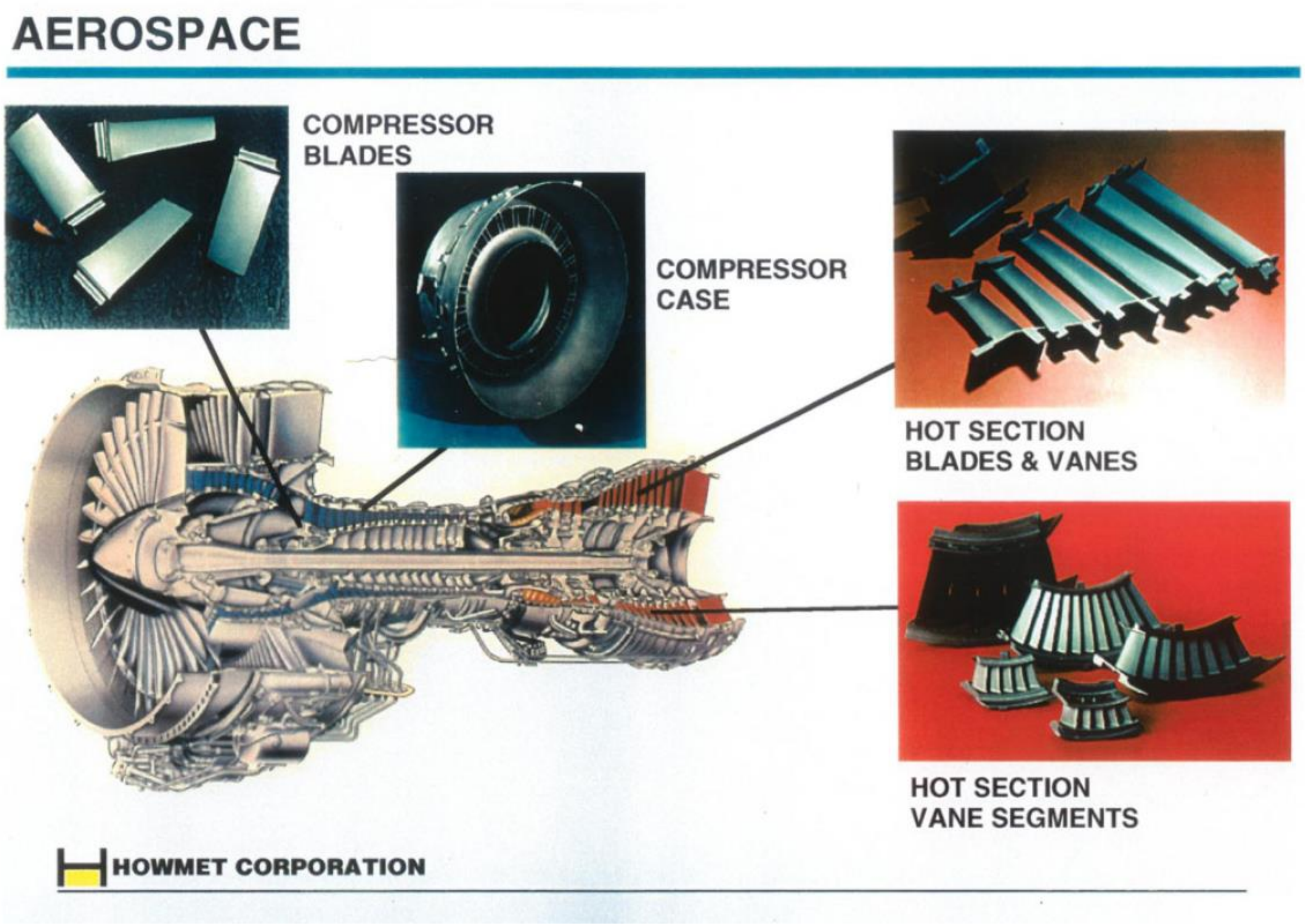
Superalloy processing begins with the fabrication of large ingots that are subsequently used for one of three major processing routes:

- ➢ remelting and subsequent investment casting,
- ➢ remelting followed by wrought processing,
- ➢ remelting to form superalloy powder that is subsequently consolidated and subjected to wrought processing operations.

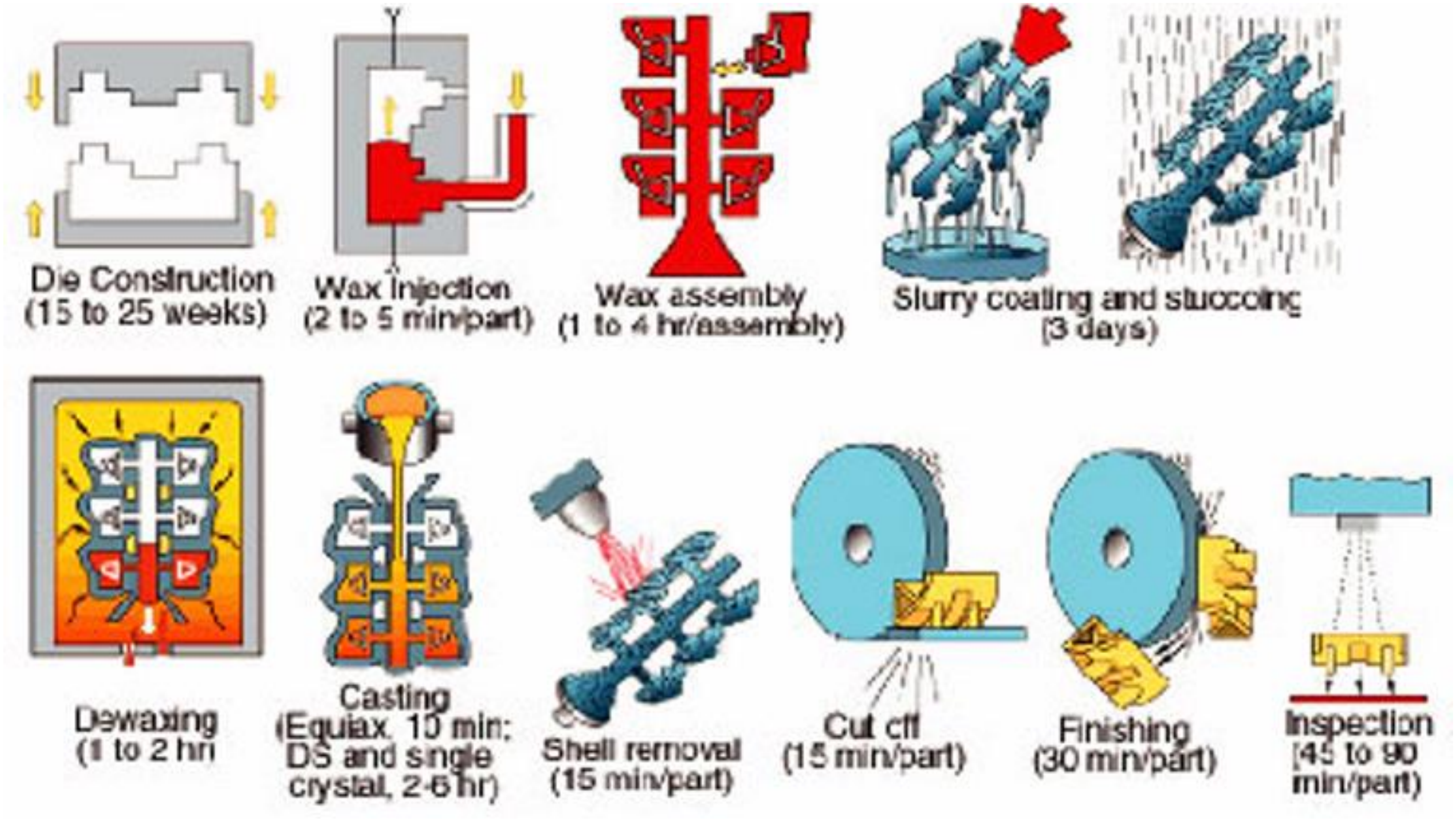


https://www.researchgate.net/publication/296013959_A_Review_on_Superalloys_and_IN718_Nickel-Based_INCONEL_Superalloy/figures?lo=1&utm_source=google&utm_medium=organic

SUPERALLOYS-CASTING

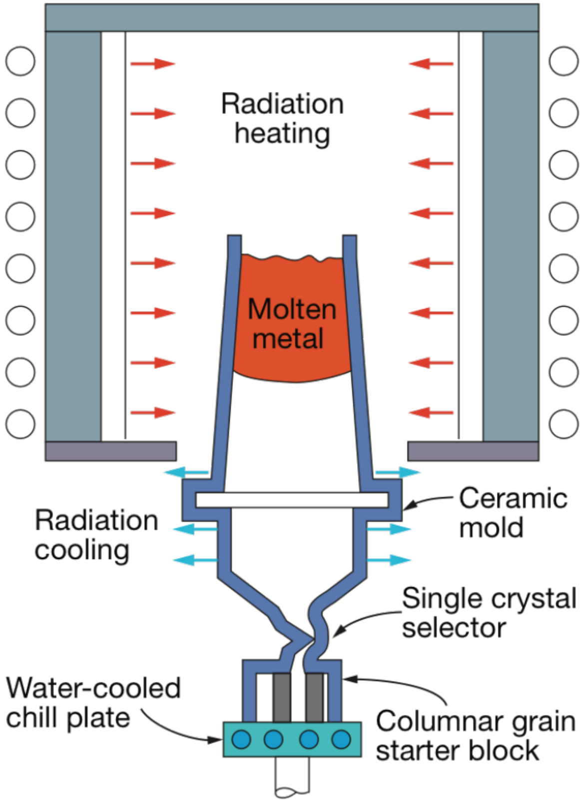


SUPERALLOYS-INVESTMENT CASTING

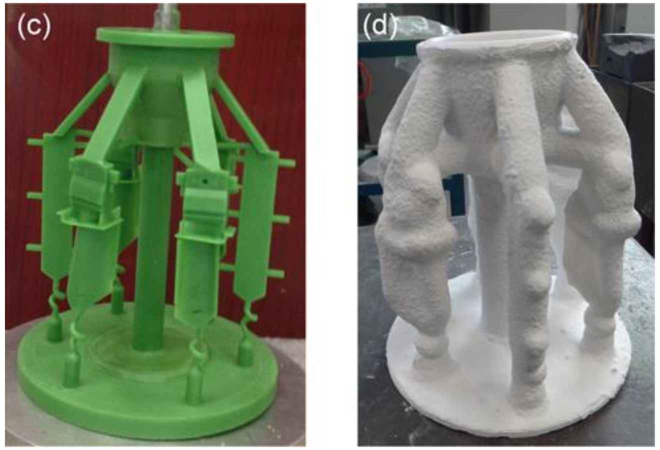


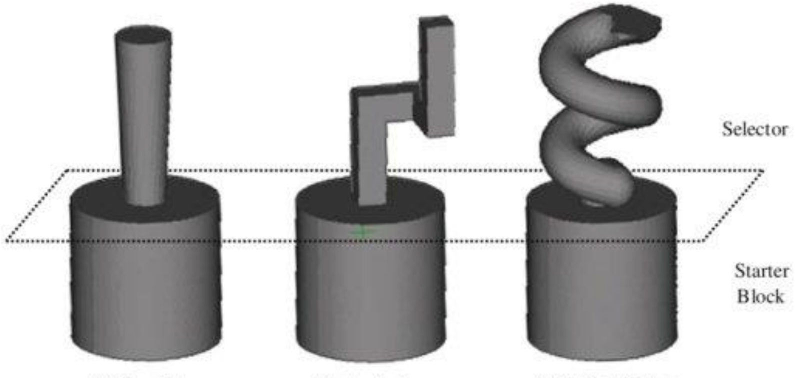
https://www.foundrymag.com/simulation-it/article/21926353/optimizing-investment-casting-by-computer-simulation

SINGLE CRYSTAL CASTING

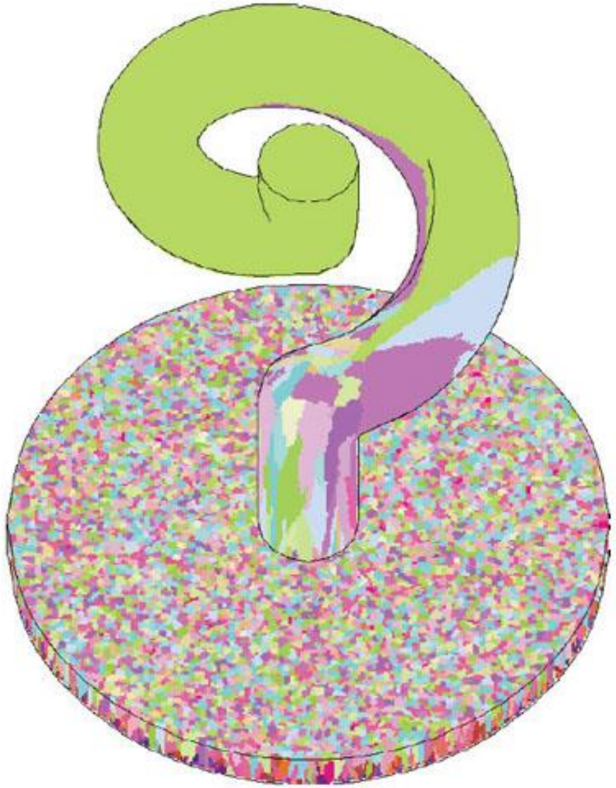


https://www.machinedesign.com/mechanical-motion-systems/article/21836518/singlecrystal-turbine-blades-earn-asme-milestone-status





(a) Restrictor (b) Angled (c) Spiral (Helix)



https://www.americanscientist.org/article/each-blade-a-single-crystal

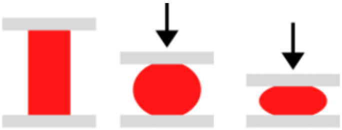
https://www.amse.org.cn/article/2019/1006-7191/1006-7191-32-11-1415.shtml

https://www.researchgate.net/publication/225654559_Grain_Selection_in_Spiral_Selectors_During_Investment_Casting_of_Single-Crystal_Turbine_Blades_Part_I_Experimental_Investigation/figures

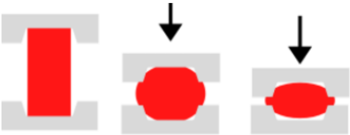
FORGING

Forging Types

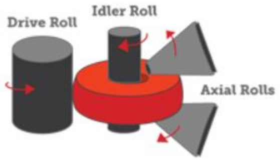
Open Die Forging



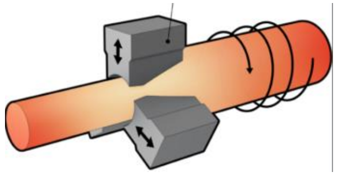
Close Die Forging



Ring Rolling



Radial Forging



Equipments

Presses

Hammer

Ring Machine

Radial Forging Machine

Semi Products

Pancake (Blank) Forgings

Near Net Shape Forgings

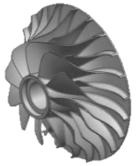
Seamless Rings

Bars & Billets

Engine Parts

Turbine Disks

Impellers & Blades



Shroud & Casings

FORGING-FORGING MATERIAL PRODUCTION & VALIDATION ROUTE

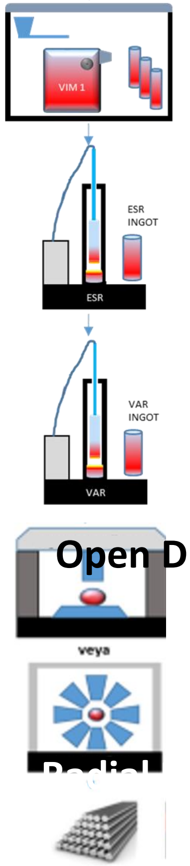
Raw material

Forging Equipments

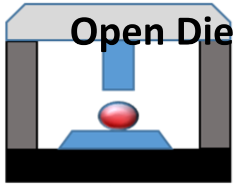
Forging Types

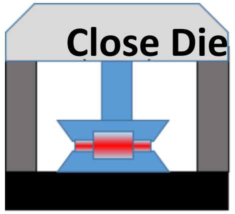
Validation Requirements

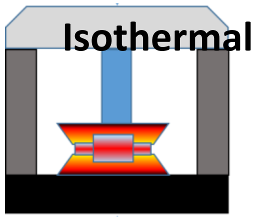
Quality Requirements

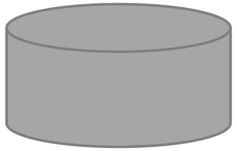


Forging Stock

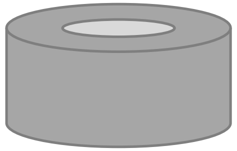






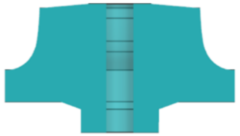


Pancake



Ring

Near Net Shape

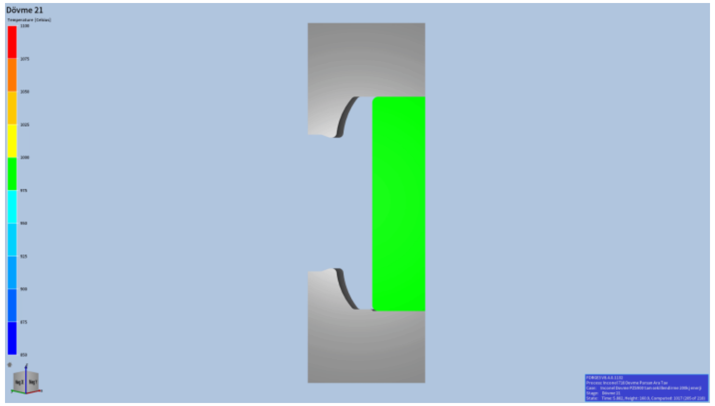


Metalurgical
- Composition
- Macrostructure
- Microstructure
- Grain Size & ALA

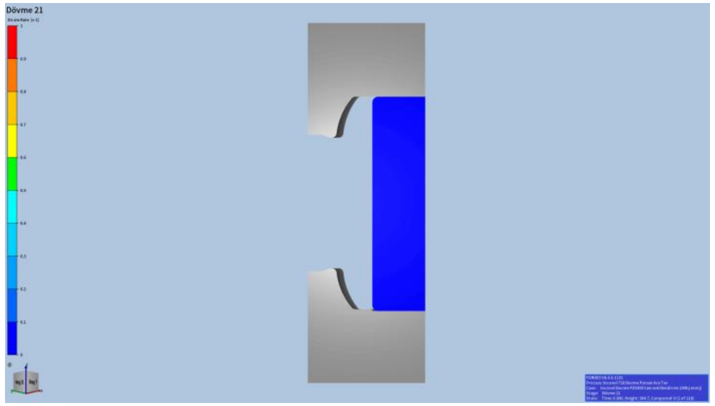
Mechanical Properties
- Tensile
- Rupture
- LCF

- Visual
- Ultrasonic Inspection
- FPI (If necessary)

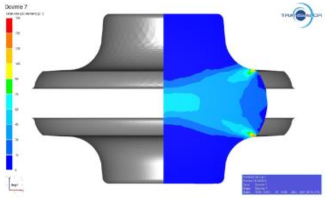
FORGINGS- FORGING DESIGN & SIMULATIONS

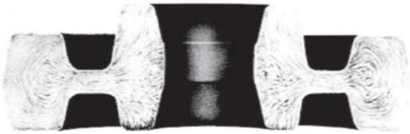


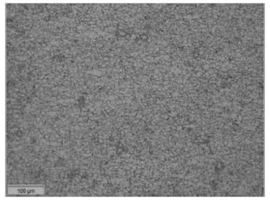
Temperature Distribution

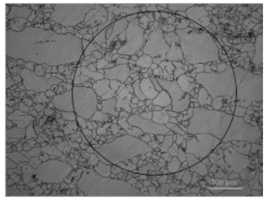


Strain Rate Distribution



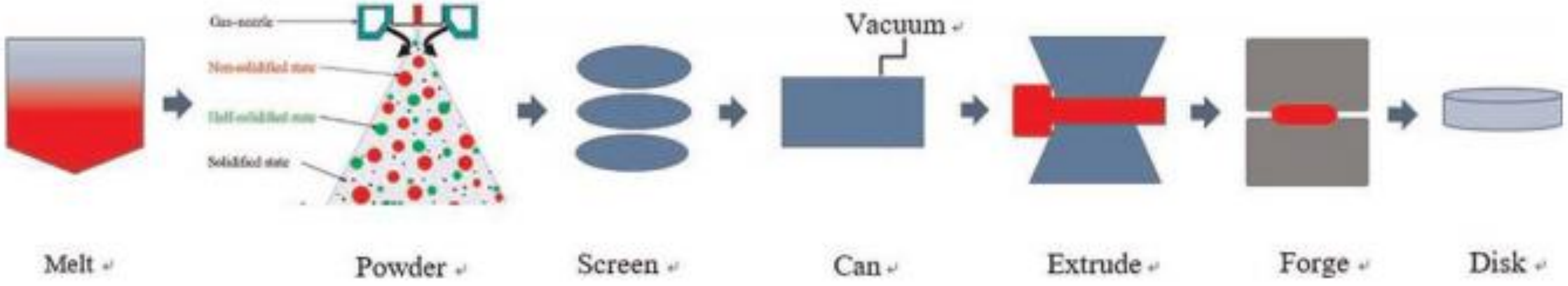


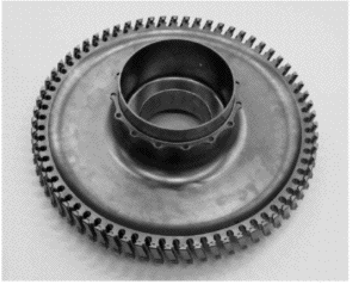


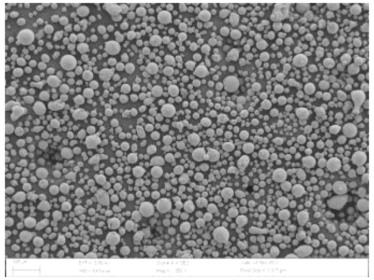


POWDER METALLURGY

- ingot metallurgy cannot be applied to the heavily alloyed grades such as Rene 95 and RR1000, since the levels of segregation arising during melt processing and the significant flow stress at temperature cause cracking during thermal-mechanical working; instead, powder-processing is preferred.
- vacuum induction melting (VIM) is used as before, followed by remelting and inert gas atomisation to produce powder – this is then sieved to remove any large non-metallic inclusions inherited from the processing. This step is important since it improves, in principle, the cleanliness of the product. To prepare a billet ready for forging, the powder is consolidated by sealing it into a can, which is then degassed and sealed, and hot isostatic pressing and/or extrusion follows.
- In principle therefore the concentration of inclusions will be lower in the powder metallurgy




Powder metallurgical aeroengine disc. Image provided by M. Hardy of Rolls-Royce.


SEM image of virgin Hastalloy powder.

https://www.hanser-elibrary.com/doi/pdf/10.3139/146.111820

https://www.sciencedirect.com/science/article/pii/B9780128140628000091

SPECIAL PROCESSES

SPECIAL PROCESSES-DEFINITIONS

Special Process: A process which may affect physical, chemical, electrical, mechanical or metallurgical properties of an material which may not be fully evaluated by nondestructive testing.

- Definitions and process content depends on engineering authority.
- There is no restrict definition for Special & Significant processes. So, there is no exact process lists for them.
- Most major processes accepted as Special Process by all OEM companies.
- International accreditation organizations (such as Nadcap) performing audits for these processes

SPECIAL PROCESSES-DEFINITIONS

Special processes can change materials';

- Grain size & morphology
- Residual stress
- Thermal conductivity
- Dislocation distribution
- Hardness
- Toughness
- Corrosion / wear / erosion / chemical attack resistance
- Tensile strength
- Creep
- Etc.

- Special processes
  - To increase durability
  - To increase life
  - To increase environmental resistance
  - To increase mechanical properties
  - May verified with dimensional, nondestructive and destructive inspection

AEROSPACE SPECIAL PROCESSES

- Abrasive Blasting
- Abrasive Finishing
- Anodizing
- Black Oxide Coating
- Brazing
- Case Hardening
- Chemical Cleaning
- Chemical Etching
- Chemical Milling and Pickling
- Diffusion Coating
- Dry Film Lube Coating
- EB (Electron Beam) Weld
- ECG (Electrochemical Grinding)
- ECM (Electrochemical Machining)
- EDM (Electrodischarge Machining)
- Heat Treatment
- HIP (Hot Isostatic Press)
- Inertia Welding
- LASER Drilling, Cutting, and Marking
- LASER Joining
- Painting- sermetal
- Passivation
- Plasma Arc Welding
- Plating
- Shot Peen
- Soldering
- Spot/Seam Welding
- Stem Drilling
- Thermal Spray
- Titanium Chemical Cleaning
- GTAW (Gas Tungsten Arc Welding)
- Pre-Spinning Of Rotor Disks And Seals
- Electron Beam Physical Vapor Deposition
- PVD Coating(e.g. TiAlN Erosion Resistant)

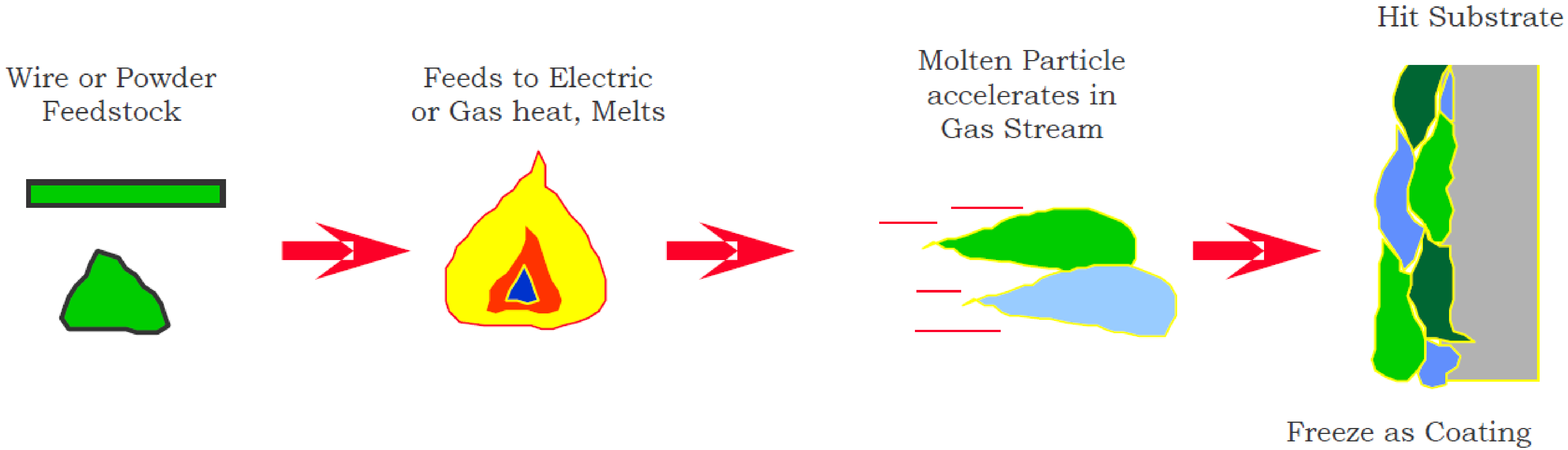
AEROSPACE SPECIAL PROCESSES

Control Functions:

- Validation
- Capability tests
- Acceptance / release tests
- Periodic tests
- Internal & external round robin programs
- Customer cross tests
- Customer process audits
- Internal and customer product audits
- Third party audits

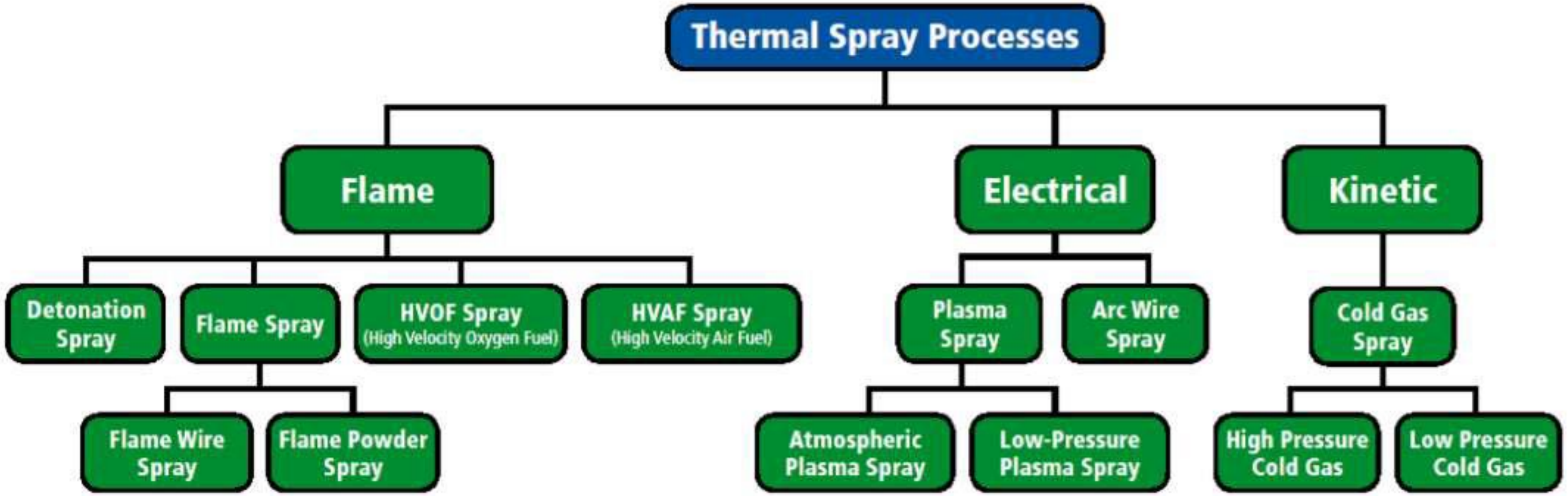
THERMAL SPRAY COATINGS

Thermal Spray is a technique by which a material is melted and transported to the substrate, cools to form a coating.

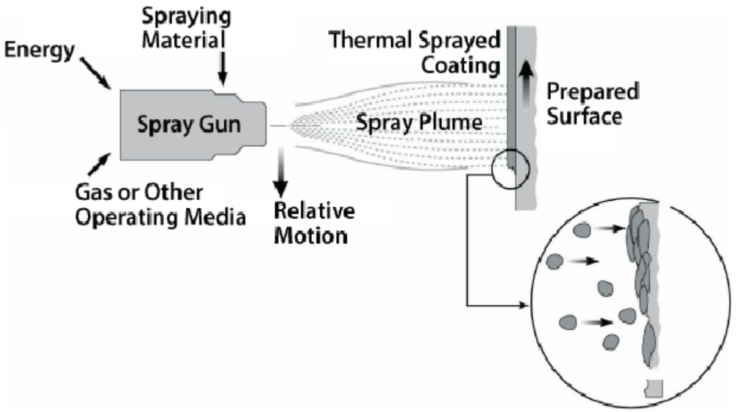


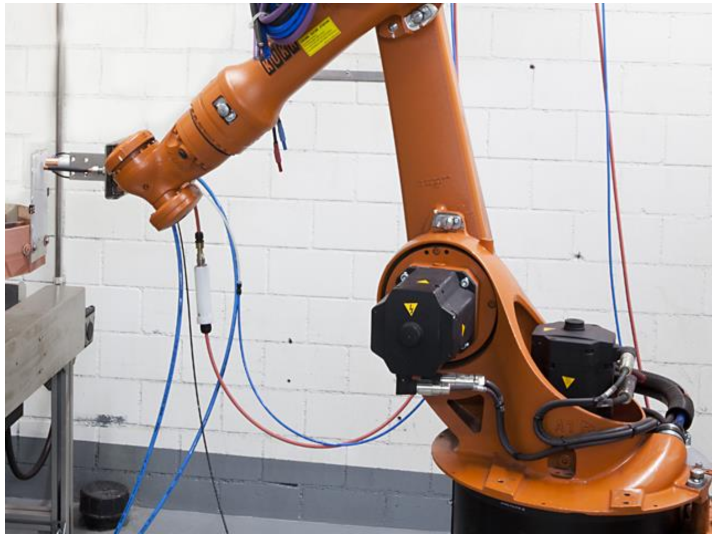
Thermal Spray comprises a number of techniques in which a heat source transforms metallic or non-metallic materials in a spray of molten or semi-molten particles that are deposited into metal substrates. These techniques are grouped as Combustion, Electric Arc, Plasma and HVOF/D-Gun.

THERMAL SPRAY COATINGS



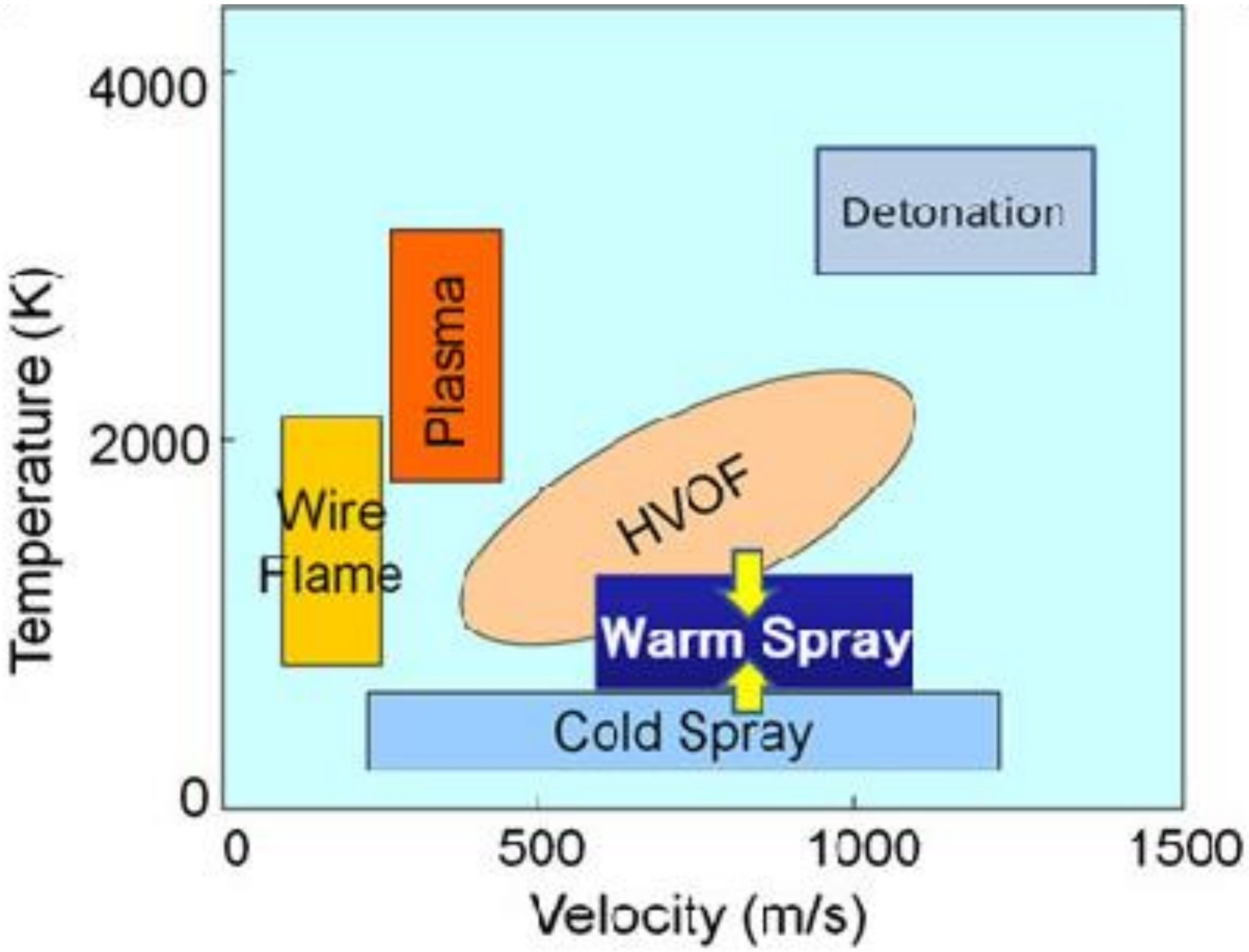
- Thermal Spray Processes
  - Flame
    - Detonation Spray
    - Flame Spray
      - Flame Wire Spray
      - Flame Powder Spray
    - HVOF Spray (High Velocity Oxygen Fuel)
    - HVAF Spray (High Velocity Air Fuel)
  - Electrical
    - Plasma Spray
      - Atmospheric Plasma Spray
      - Low-Pressure Plasma Spray
    - Arc Wire Spray
  - Kinetic
    - Cold Gas Spray
      - High Pressure Cold Gas
      - Low Pressure Cold Gas





https://www.semanticscholar.org/paper/A-Review-on-Thermal-Spray-Coating-Processes-Amin/6ce8974a03f6b185beff70db3aa45c332cf6d67a

THERMAL SPRAY COATINGS



THERMAL SPRAY COATINGS

Coating types used in aerospace industry;

- Thermal Barrier Coatings

  Thermal shock, thermal fatigue, hot corrosion

- Anti-wear Coatings

  Mechanical, chemical wear; fretting, sliding, abrasion, erosion, corrosion

- Abradable Coatings

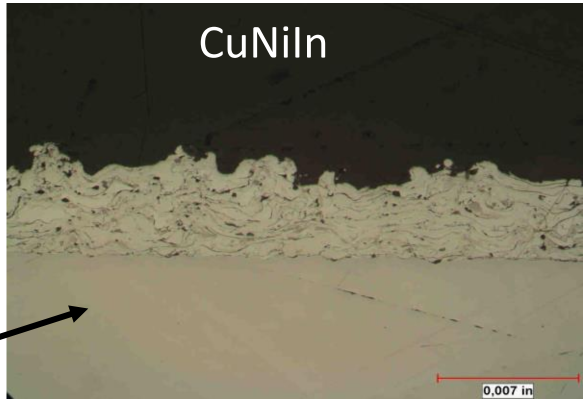
  Clearance, bearing air seals, oil sealing, corrosion resistance

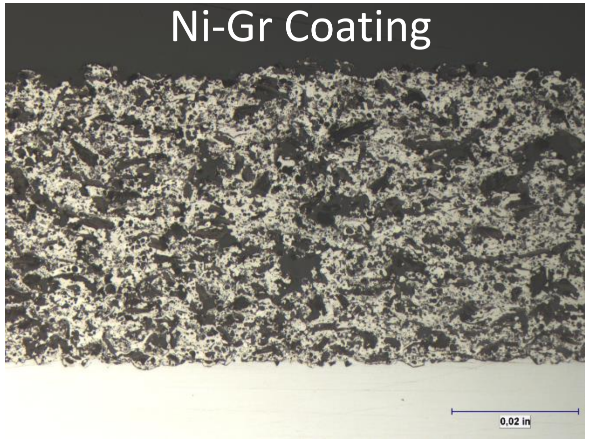
- Abrasive Coatings

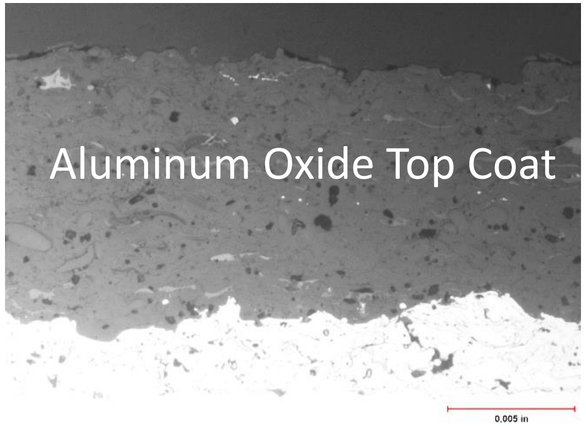
  Sealing

- Restoration Coatings

  Build-up restorations







THERMAL BARRIER COATINGS

COATINGS

- YTTRIA STABILIZED ZIRCONIA
- MAGNESIUM STABILIZED ZIRCONIA

COATING TESTS

- METALLOGRAPHY
- BEND TEST
- THERMAL SHOCK JETS TEST
- FURNACE CYCLE TEST

Yttria-stabilized zirconia and magnesium-stabilized zirconia are the main TBC coatings. These coatings are primarily used on combustors and flameholders.

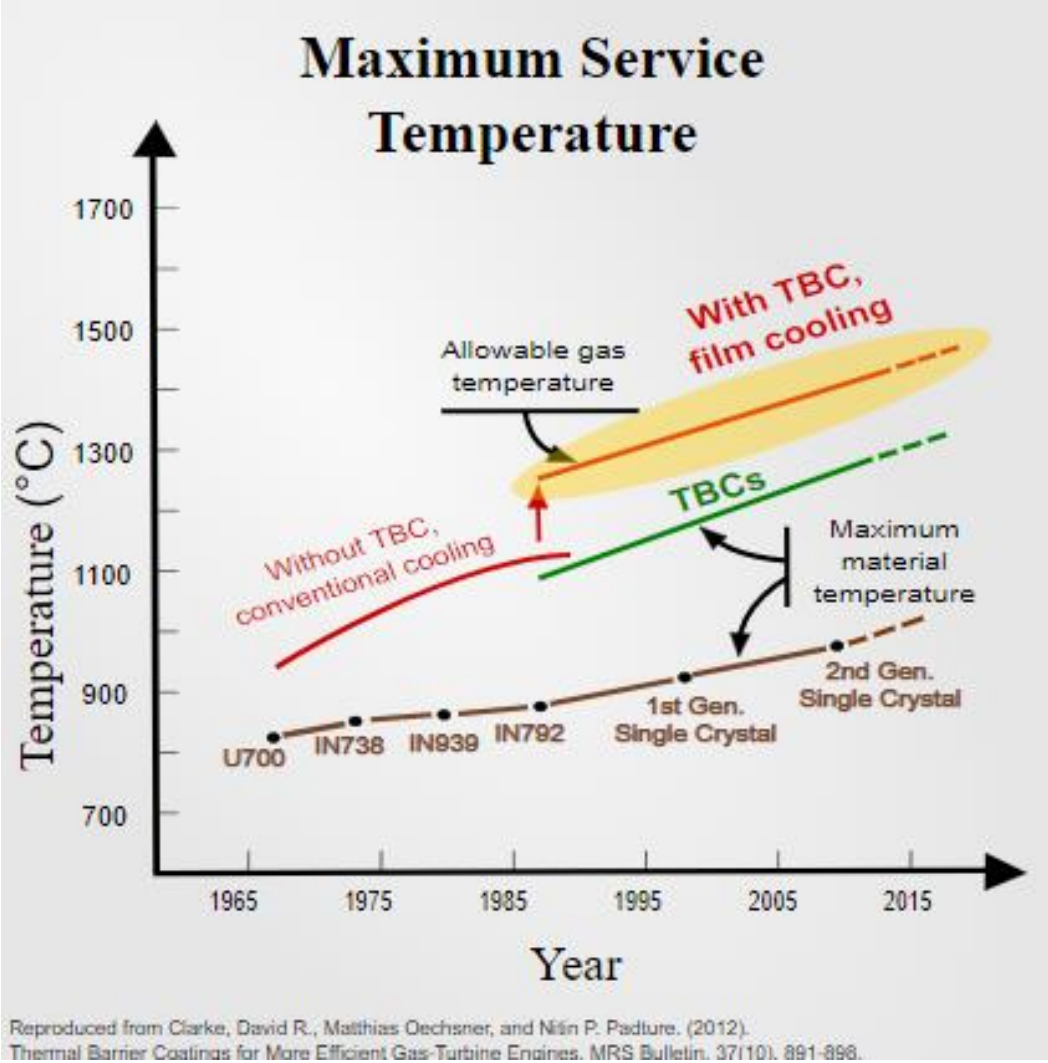
Yttria Stabilized Zirconia

- used as thermal barrier coating on high temperature regions of engine.
- provides thermal insulation and corrosion resistance to applied components.
- applied with the air plasma spray method. The coating system combines a NiCrAlY bond coat and a yttria stabilized zirconia top coat.
- Metallographic evaluation is primarily aimed at coating porosity. Low thermal conductivity of ceramic top coat material and coating porosity content is the main insulation factor of coating.

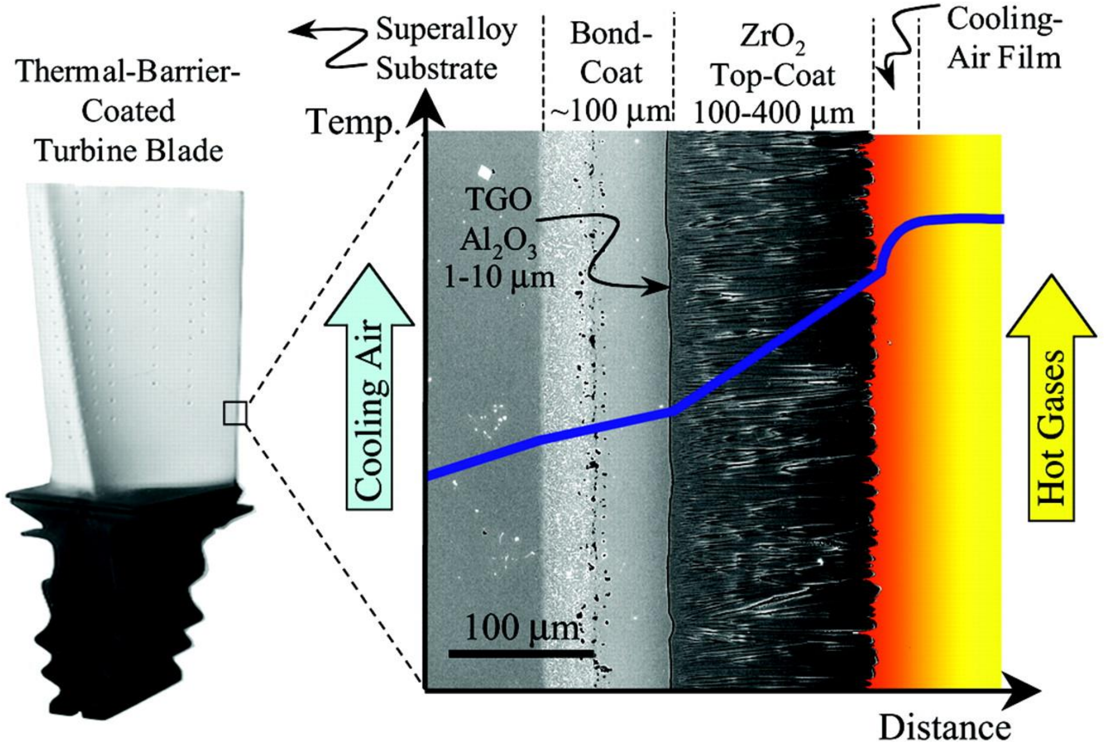
Typical Microstructure Characteristics

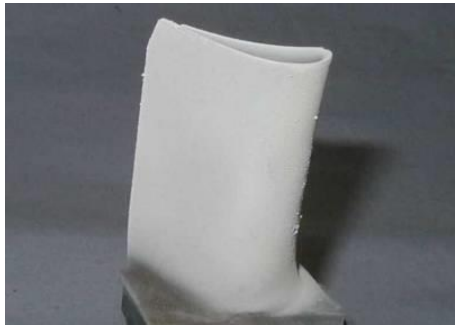
- a ceramic coating with low fracture toghness.
- The microstructural characteristics are to be evaluated are porosity, interface condition, delamination, cracks and pull-out. The coating is very sensitive to diamond polishing, which can cause coating fracturing of the ceramic top coat.

THERMAL BARRIER COATINGS



Reproduced from Clarke, David R., Matthias Oechsner, and Nitin P. Padture. (2012). Thermal Barrier Coatings for More Efficient Gas-Turbine Engines. MRS Bulletin, 37(10), 891-898.

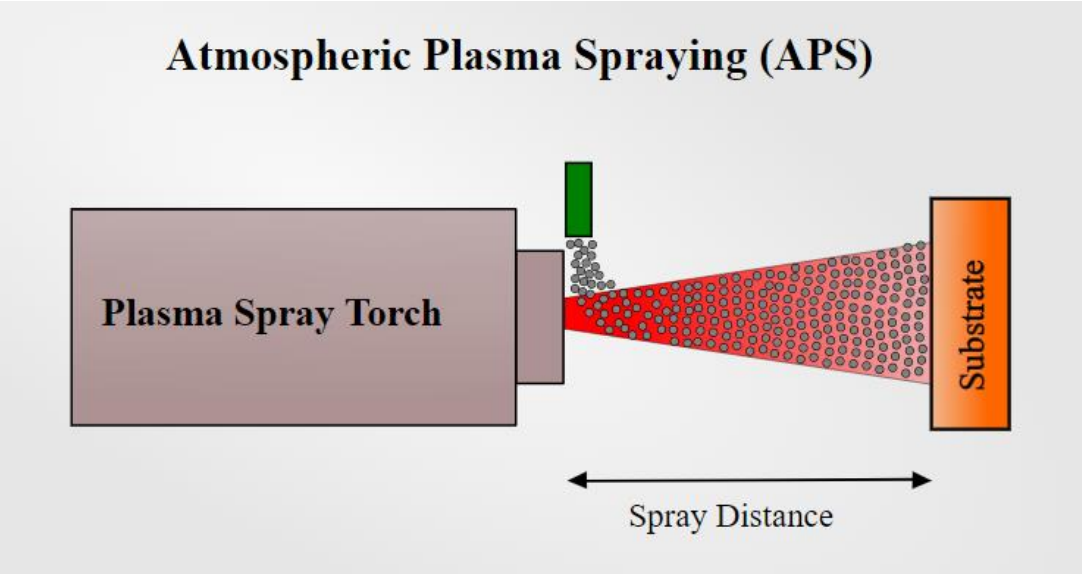


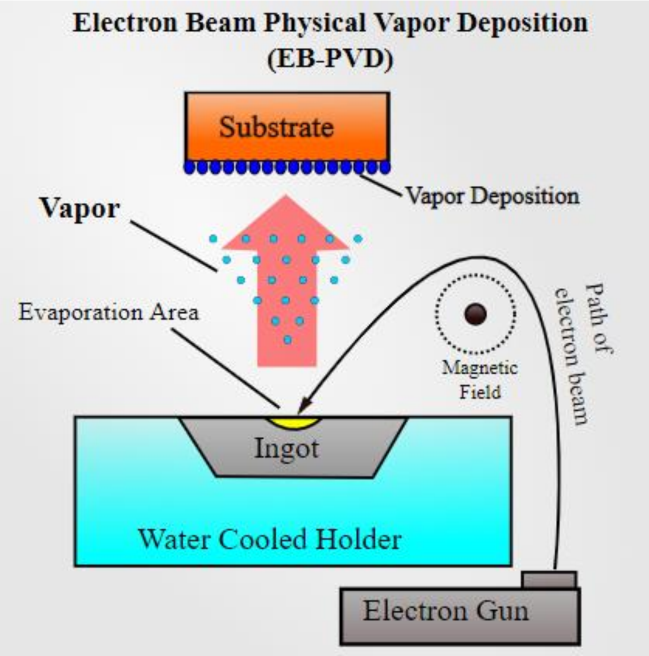


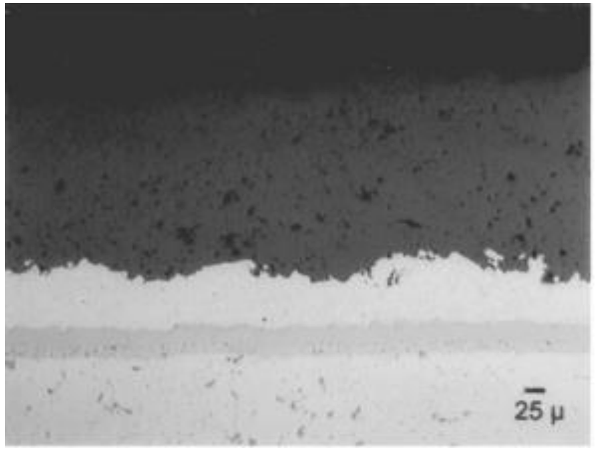
https://science.sciencemag.org/content/296/5566/280

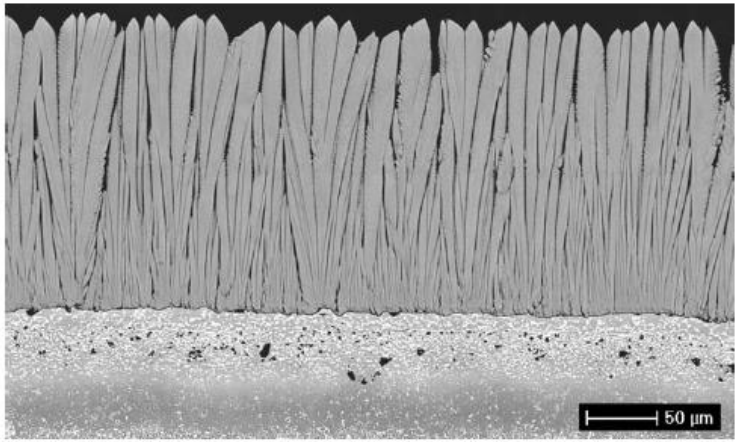
https://www.ucl.ac.uk/institute-for-materials-discovery/research/structural-coatings/thermal-barrier-coatings

THERMAL BARRIER COATINGS





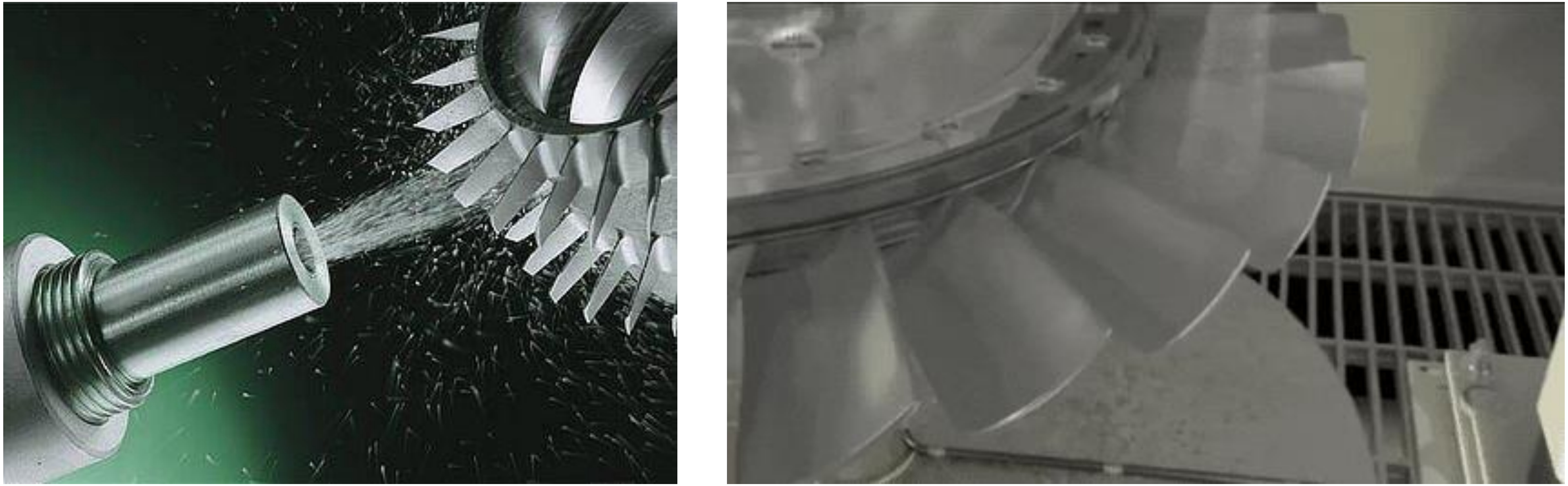




https://msestudent.com/what-are-thermal-barrier-coatings-tbcs-materials-manufacturing-methods-and-applications/

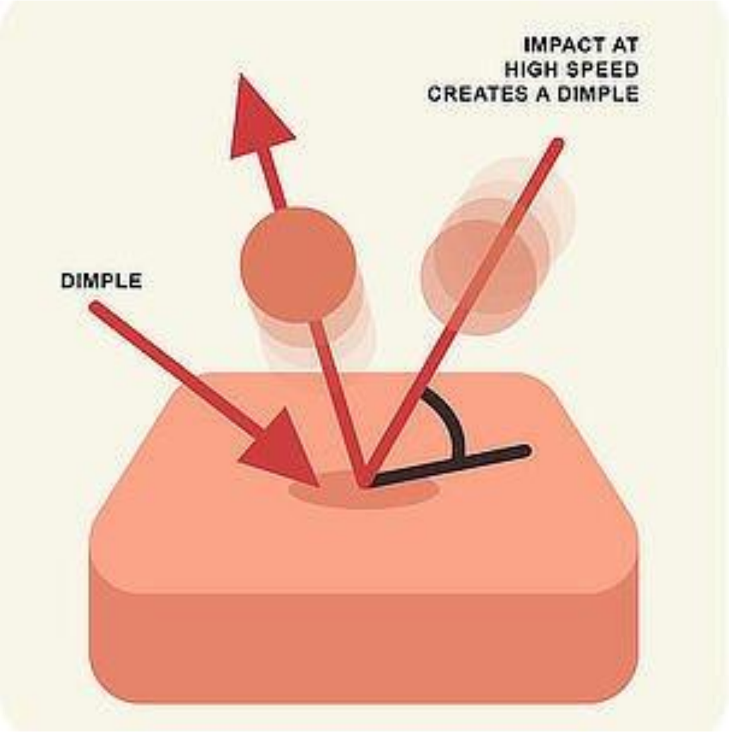
SHOT PEENING

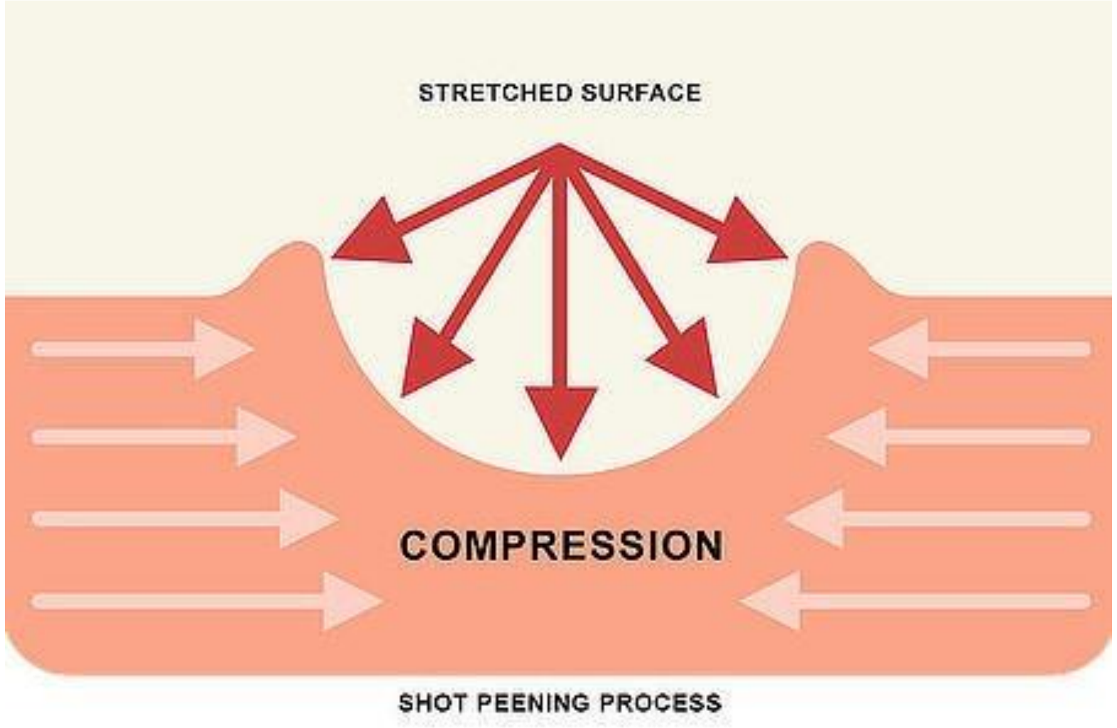
Shot peening is a method of cold working in which compressive stresses are induced in the exposed surface layers of metallic parts by the impingement of a stream of shot, directed at the metal surface at high velocity under controlled conditions.



SHOT PEENING

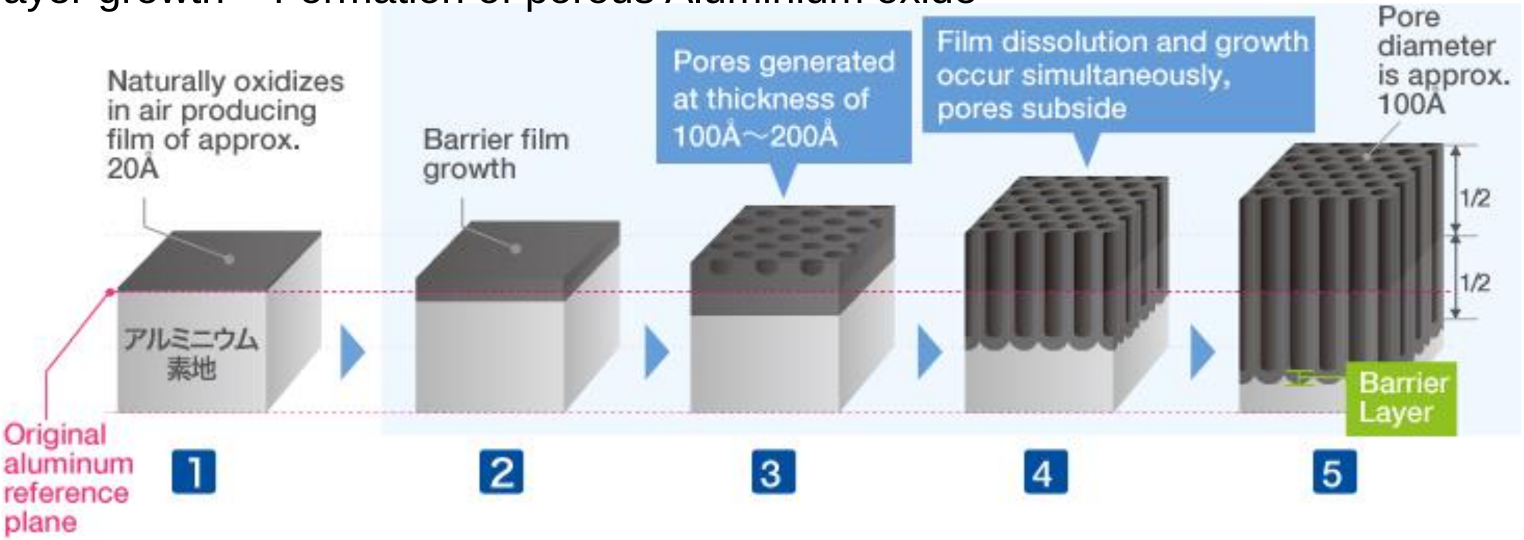
- Shot peening essentially uses small shots to make small plastic deformations in the metal surface.
- When these shots make contact with the metal the surface, they create a tiny crater in the part of the metal that is under stress.
- Generation of compresive stressed layer
- Compressive stresses act as a counterbalance to the tensile surface stresses present in many metallic components, and they inhibit the initiation and propagation of fatigue cracks that occur under service loads.

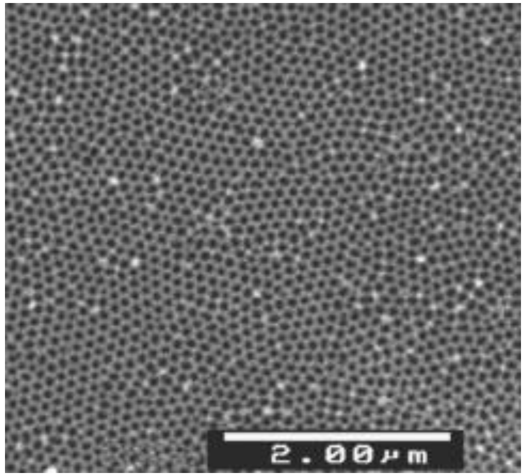




ANODIZING

Anodizing layer growth – Formation of porous Aluminium oxide

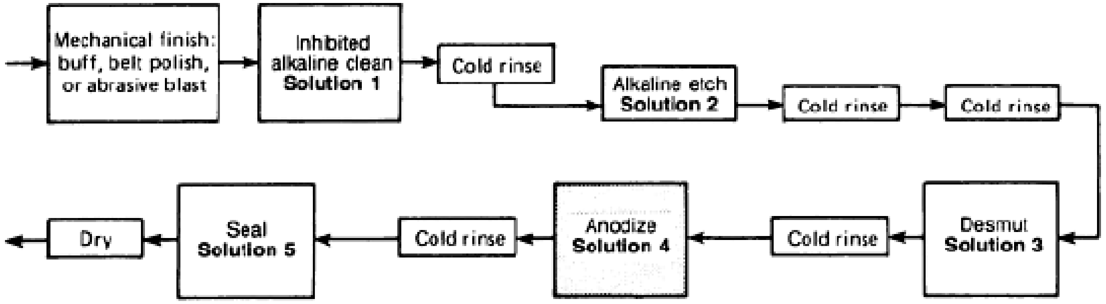




Miyaki Co. LTD., About anodizing http://125.206.173.248/global/aluminum/anodized-aluminum.html

- ➢ Anodizing is applied to;
- ➢ Increase corrosion resistance
- ➢ Improve decorative appearance
- ➢ Increase abrasion resistance
- ➢ Increase paint adhesion
- ➢ Improve adhesive bonding
- ➢ Improve lubricity
- ➢ Provide electrical insulation
- ➢ Increase emissivity

Typical anodizing process flow chart



Anodizing have detrimental effect on fatigue properties !

ASM Handbook, *Surface Engineering*, Vol 05, page 1416-1417

WELDING

Welding is a fabrication process whereby two or more parts are fused together by means of heat, pressure or both forming a join as the parts cool. Welding is usually used on metals and thermoplastics.

Major difference of welding from other metal-joining techniques such as brazing and soldering is melting base metal.

Not all metals are suitable for welding process and they may not be join properly with welding applications.

Pressure

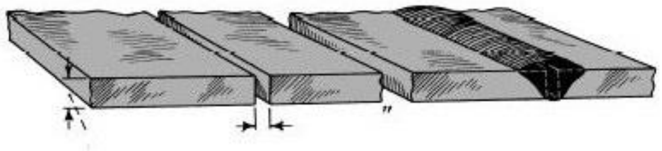
Heat

Hot / Cold

With pressure / Without pressure

With filler / Without filler

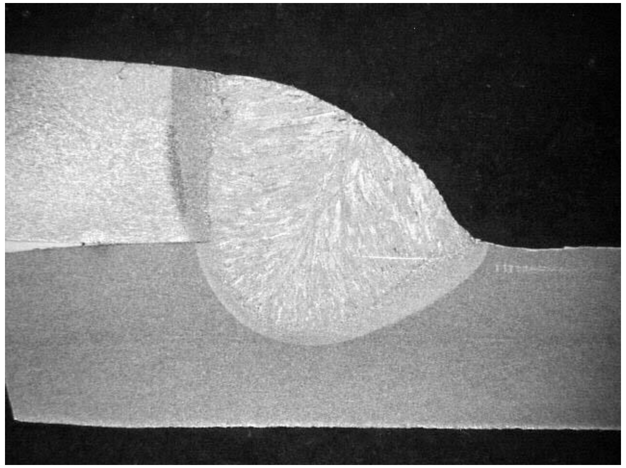
Manual / Automated

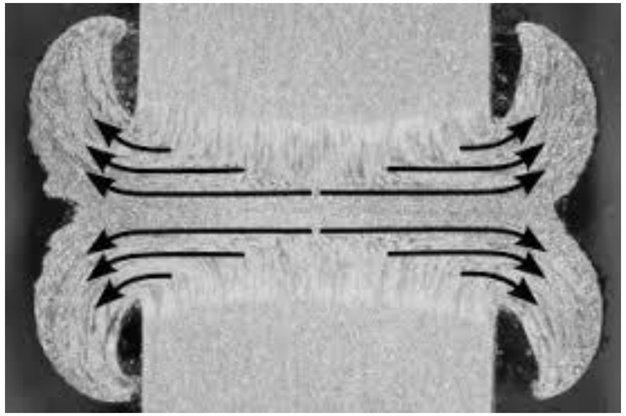


WELDING

two major categories

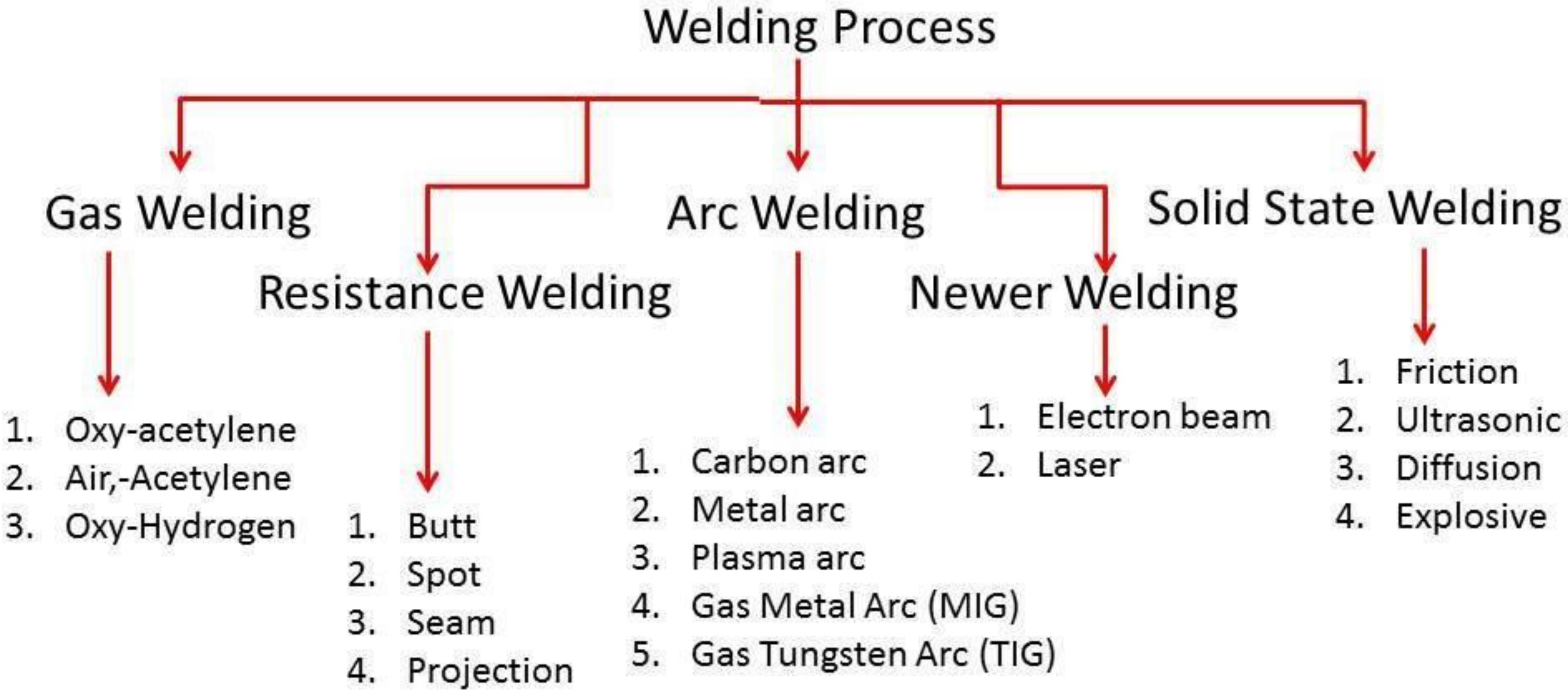
- Fusion welding
  - Joining processes that melt the base metals
  - In many fusion welding operations, a filler metal is added to the molten pool to facilitate the process and provide bulk and added strength to the welded joint
  - A fusion welding operation in which no filler metal is added is called an autogenous weld





- Solid state welding
  - Joining processes in which coalescence results from application of pressure alone or a combination of heat and pressure
  - If heat is used, temperature is below melting point of metals being welded
  - No filler metal is added in solid state welding

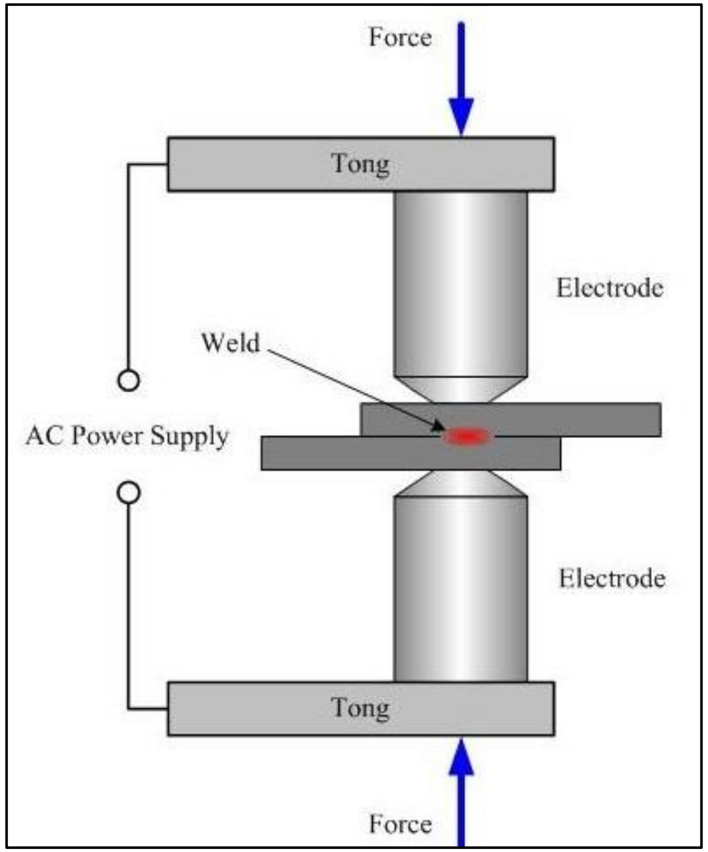
WELDING



Welding Process

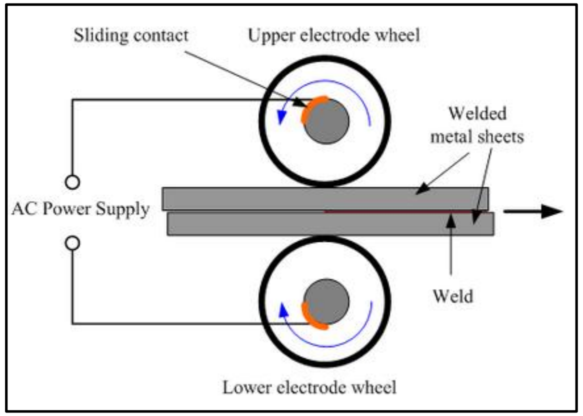
- Gas Welding
  1. Oxy-acetylene
  2. Air,-Acetylene
  3. Oxy-Hydrogen
- Resistance Welding
  1. Butt
  2. Spot
  3. Seam
  4. Projection
- Arc Welding
  1. Carbon arc
  2. Metal arc
  3. Plasma arc
  4. Gas Metal Arc (MIG)
  5. Gas Tungsten Arc (TIG)
- Newer Welding
  1. Electron beam
  2. Laser
- Solid State Welding
  1. Friction
  2. Ultrasonic
  3. Diffusion
  4. Explosive

RESISTANCE SPOT WELDING/ RESISTANCE SEAM WELDING



achieves coalescence using heat from electrical resistance to the flow of a current passing between the faying surfaces of two parts held together under pressure.

- Generally used for sheet materials
- Filler material or consumable is not required
- Very short process time
- A reliable electro-mechanical joint is formed
- Commonly used in;
  - Automotive
  - Aerospace
  - Home appliances
  - Radiator
  - Electronics

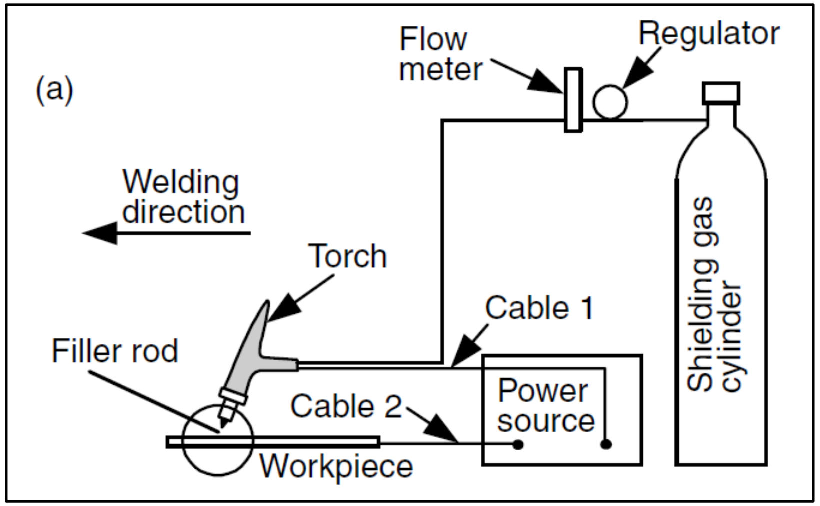


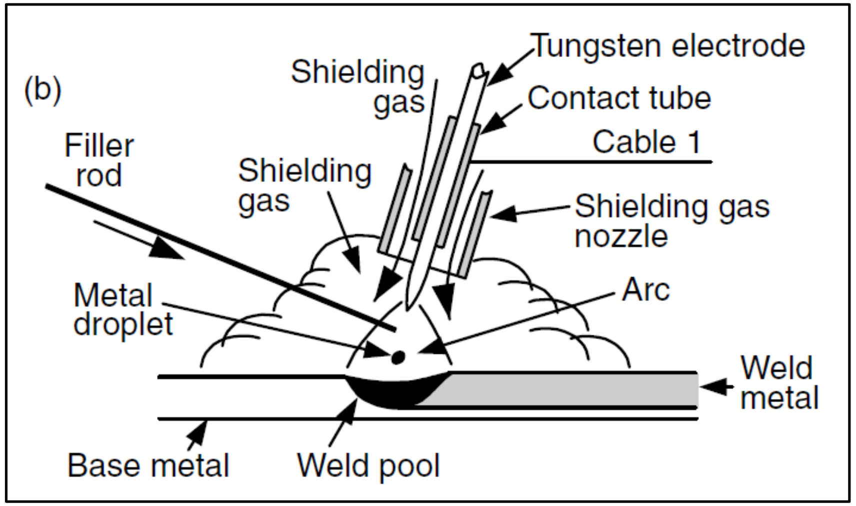
Differences between spot and seam welding;

- Seam welding can provide continuous, overlapped and intermittent welds
- Seam welding can provide leakproof joint
- Seam welding restricted to a straight line or uniformly curved line
- Seam welding is faster than spot welding

GAS TUNGSTEN ARC WELDING (TUNGSTEN INERT GAS WELDING) TIG/GTAW

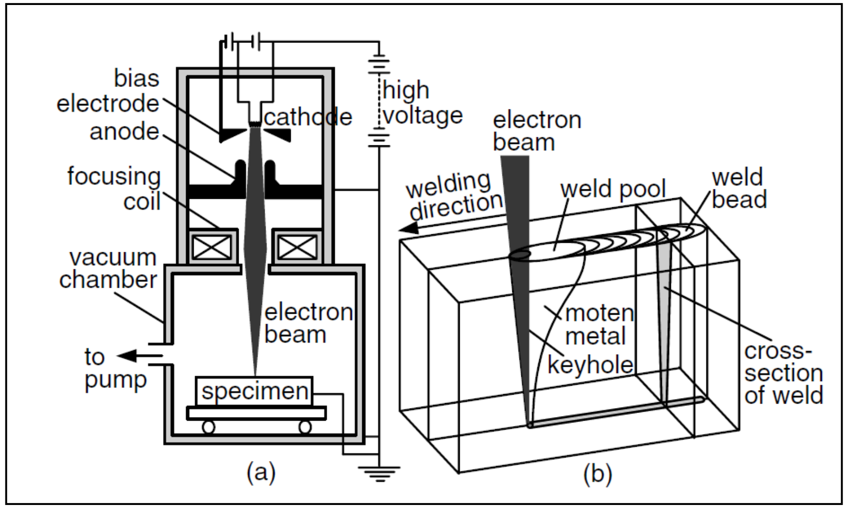
- arc welding process using an arc between a tungsten electrode (non-consumable) and the weld pool
- The process is used with shielding gas and without the application of pressure. Since argon is cheaper and heavier than other inert gasses, argon is used generally as shielding gas
- Usage of shielding gas is an advantage for welding of reactive metals (i.e. Aluminium, titanium, zirconium)
- GTAW is considered as the most challenging welding method to master
- Provides high quality weld structure when performed properly

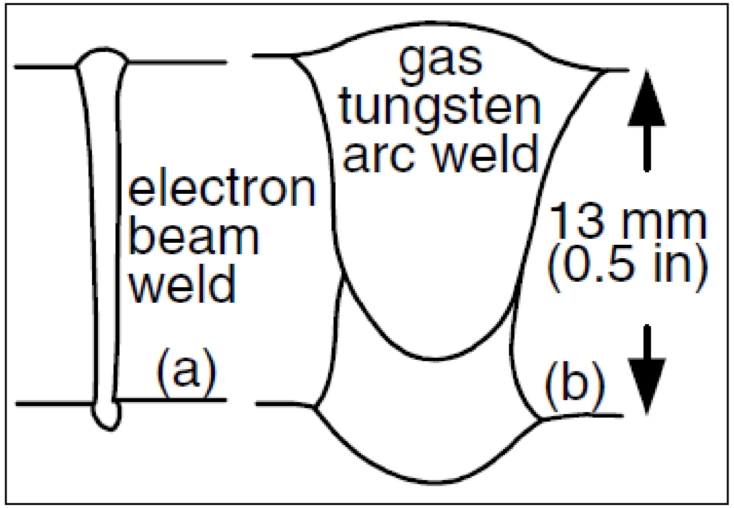




ELECTRON BEAM WELDING – EBW

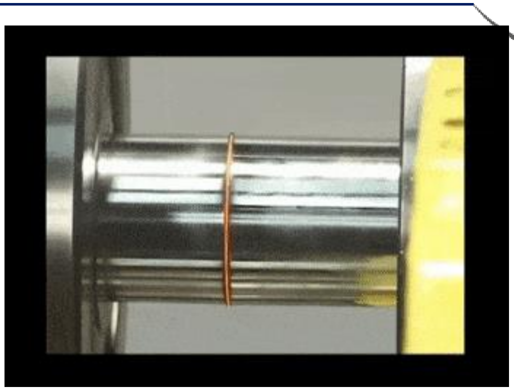
- a process that produces coalescence with a concentrated beam composed primarily of high-velocity electrons, impinging on the joint. The process is used without shielding gas and without the application of pressure. Process is performed in a vacuum chamber.
- A high energy and extremely focused beam of electrons is used to join metals, with no filler metal required. This approach results in a small heat-affected zone with minimal distortion, while the bulk of the assembly remains cold and stable.
- The welds produced are narrow and deep (up to 30 mm) and as it takes place in a vacuum, process can achieve almost pore-free welds.
- Computer controls ensure minimal operator dependence and a high degree of reproducibility.

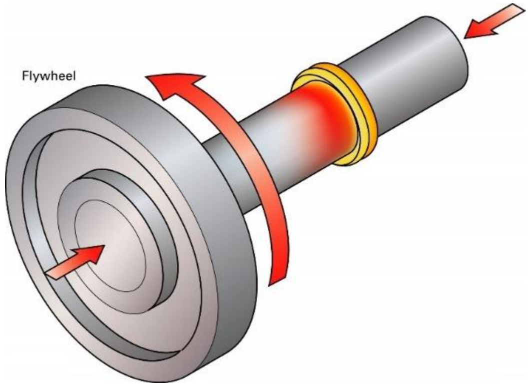


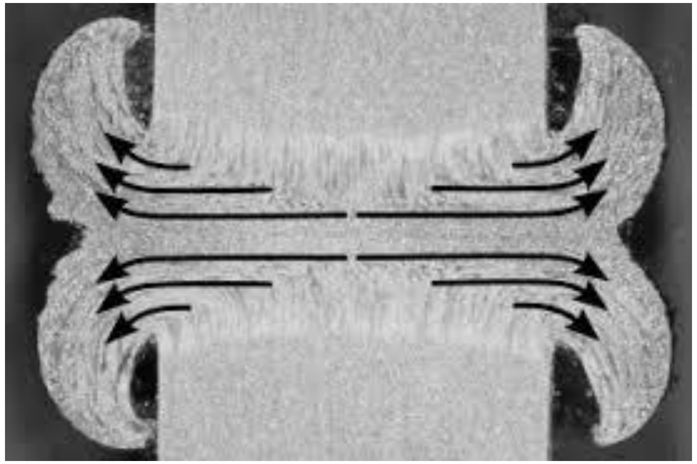


ROTARY FRICTION WELDING (INERTIA WELDING)

- a solid-state joining process which works by rotating one work piece relative to another while under a compressive axial force.
- Friction produces heat, causing the interface material to plasticize.
- The compressive force displaces the plasticized material from the interface
- Friction welding shortens the work pieces
- The weld remains in the solid-state, avoiding many of the defects associated with melting and solidification during fusion welding. The distortion of the welded component is also reduced.
- The process has lower peak temperatures than fusion welding, reducing intermetallic formation and allowing for a range of dissimilar materials to be joined.
- The process does not require a filler metal, flux and shielding gas.
- The process is easily automated, making the process highly repeatable and not dependent on human influence, resulting in very low defect rates.
- When used to fabricate preforms, the material usage and manufacturing costs are reduced when compared to subtractive techniques (eg machining from ingots and forgings).
- High investment required for equipment and tooling.







TESTING

The successful employment of metals in engineering applications relies on the ability of the metal to meet design and service requirements and to be fabricated to the proper dimensions. The capability of a metal to meet these requirements is determined by the mechanical and physical properties of the metal.

Physical: not requiring the application of an external mechanical force
-Density
-Magnetic
-Thermal Conductivity
-Thermal Diffusivity
-Electrical
-Specific Heat
-Thermal Expansion
-Etc.

Mechanical:relationship between forces acting on a material and the resistance of the material to deformation and fracture
-Hardness
-Yield & UTS
-Elastic Modulus
-Creep
-Fatigue
-Crack Growth
-Fracture Toughness
-Etc.

TUSAŞ MOTOR SANAYİİ A.Ş.
TUSAŞ ENGINE INDUSTRIES, INC.

GÜCÜN KAYNAĞI

TEŞEKKÜRLER

TASNİF DIŞI

TUSAŞ MOTOR SANAYİİ A.Ş.
TUSAŞ ENGINE INDUSTRIES INC.

TUSAS ENGINE INDUSTRIES INC.

TEKNOFEST
HAVACILIK, UZAY VE TEKNOLOJİ FESTİVALİ

Art Yakıcı (Afterburner) Mekanik Tasarım Teknik Eğitim

10.01.2023

Plan

1- Ark Yakıcı (Afterburner)

- Parçaların Tanıtılması
- Parça Görevleri
- Tasarım Kriterleri

2- Mekanik Tasarım Kriterleri

- Dayanım (Strength)
- Ömür (LCF/HCF)
- Sürünme (Creep)
- Tireşim (Vibration)
- Çatlak İlerleme (Crack Propagation)
- Yüksek Basınç Durumu (Overpressure)
- Civatalı Bağlantı Tasarımı

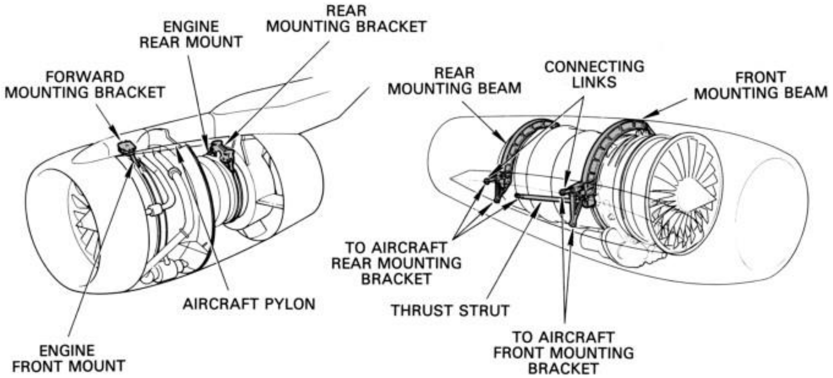
Mekanik Tasarım Ekibi

Abdullah Cenk Işık	Mekanik Tasarım Şef Mühendisi
Ahmet Kaan Zayim	Kıdemli Mekanik Tasarım Mühendisi
Anıl Türkseven	Mekanik Tasarım Mühendisi
Muharrem Çakmak	Mekanik Tasarım Mühendisi
Yasemin Sarıoğlu	Mekanik Tasarım Mühendisi

Sabit Parçalar (Static Structures)

Muhafaza (Casing)

Taşıyıcı Yapı (Frame)



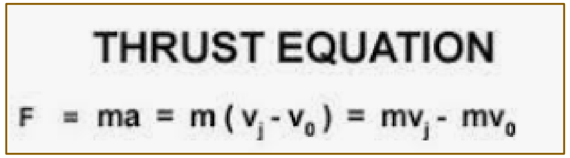
Askı Yapısı (Mount)

Fonksiyonları;

- Motorun bütünlüğünü sağlamak,
- Akışa yön vermek,
- Rotor parçalarını rulmanlar vasıtasıyla desteklemek,
- Bağlantı ve askı ara yüzü oluşturmak.

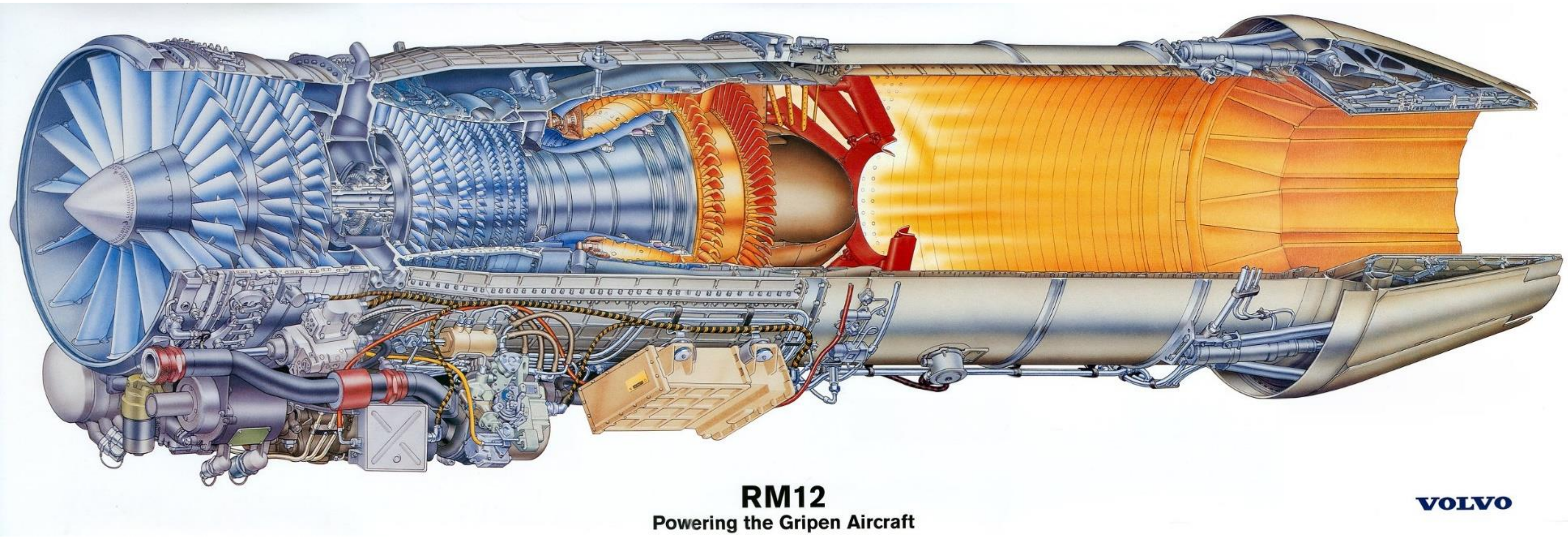
Afterburner Fonksiyonu

Art Yakıcı: Türbinden çıkan yanmamış gazları ikincil bir yanmayla tekrar yakarak, gazları hızlandırır ve çok yüksek itki artışı sağlar.

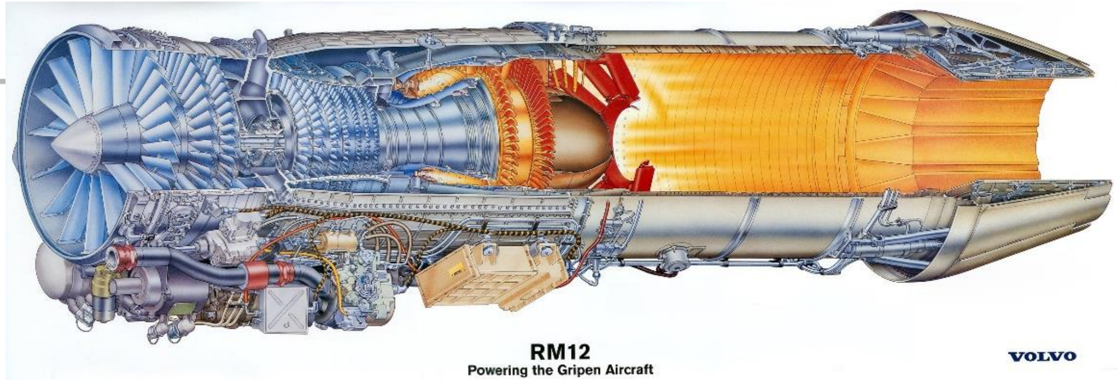


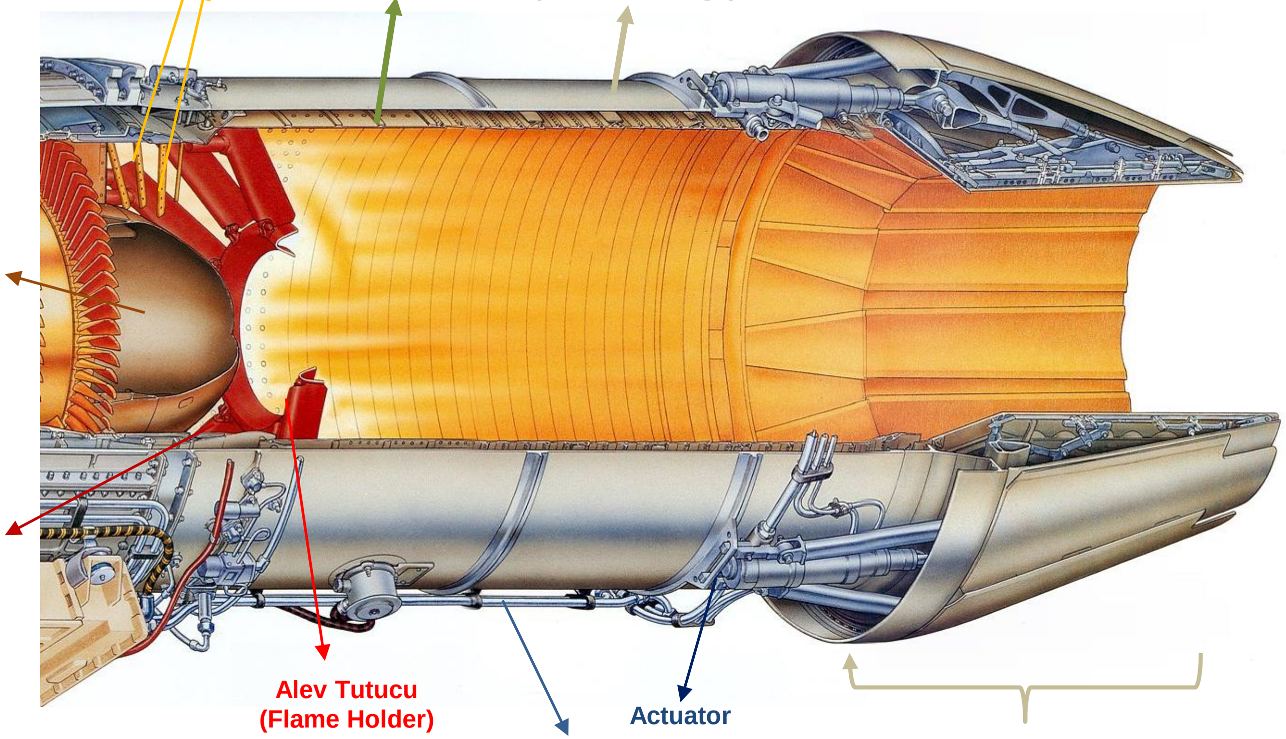
THRUST EQUATION

$$F = ma = m(v_j - v_0) = mv_j - mv_0$$



Afterburner Parçaları





Yakıt Enjektörleri
(Fuel Injectors)

İç Gömlek
(Liner)

Dış Gömlek
(Ducts / Casings)

Difüzör
(Diffuser Cone)

Ateşleyici
(Igniter)

Alev Tutucu
(Flame Holder)

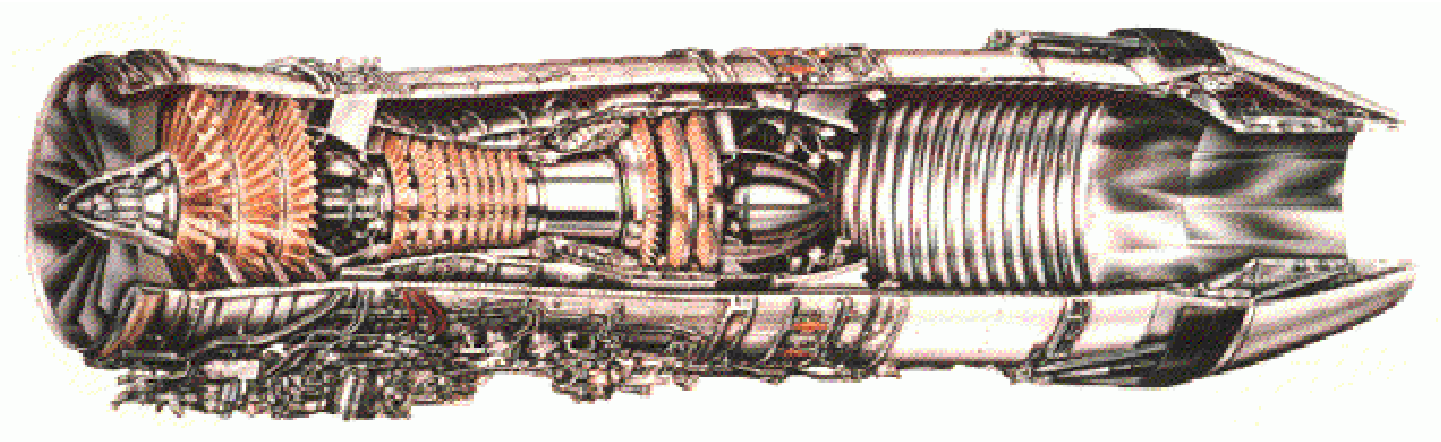
Actuator

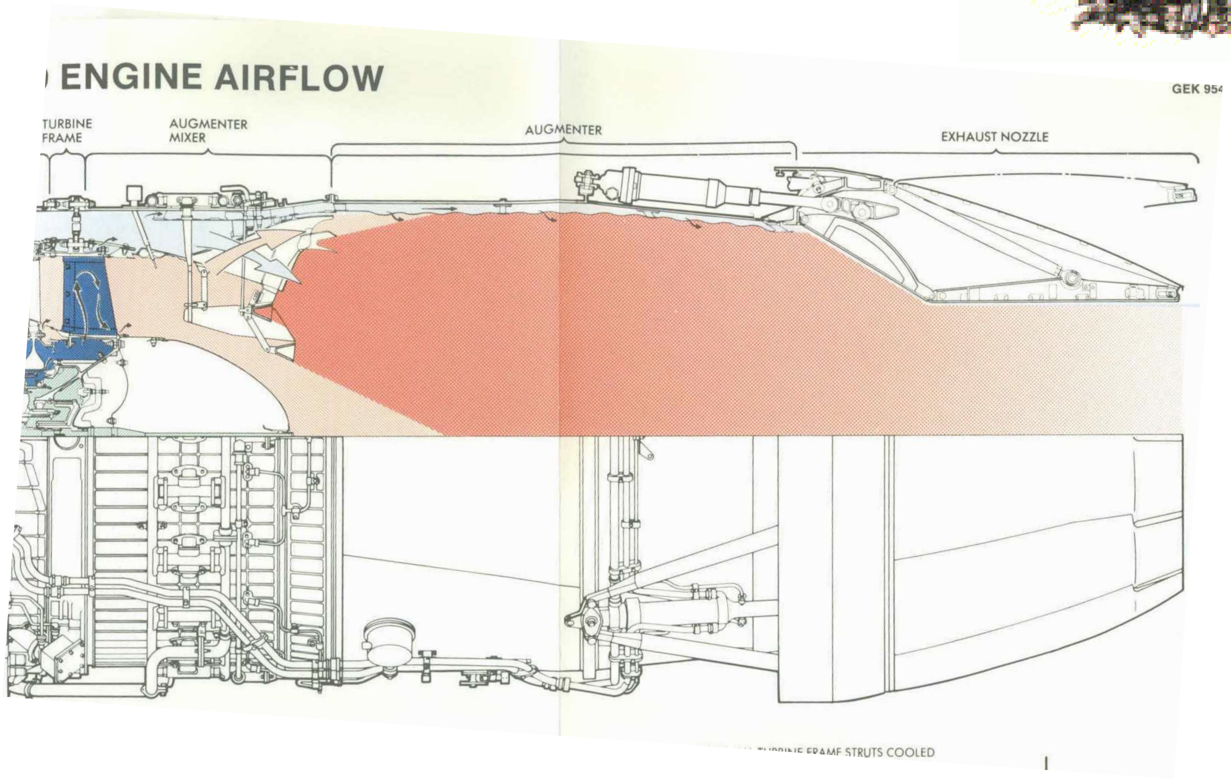
Yakıt/Yağ Hattı
(Fuel/Oil Supply System)

Değişken Yakınsak/Iraksak Nozül
(Variable Exhaust Nozzle)

Örnekler

F110





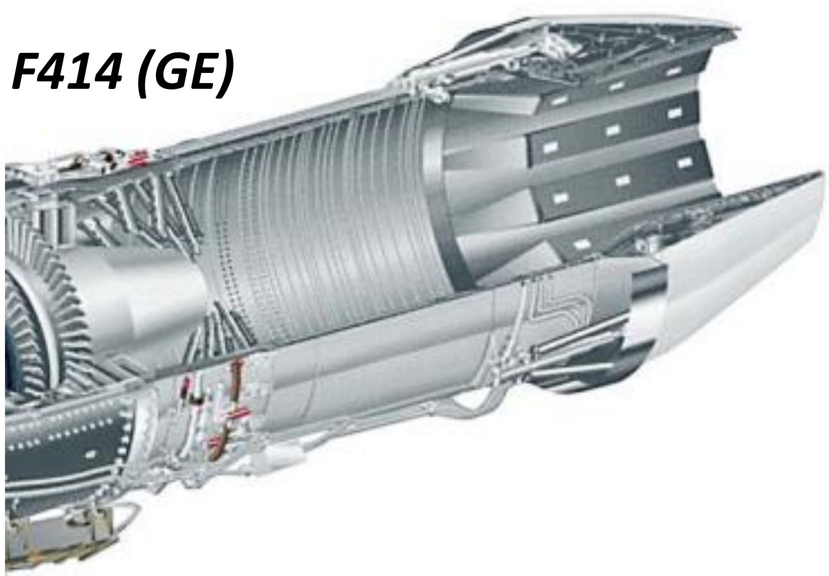
Bypass oranı = 0.76:1

Dry Power = 74 kN

Wet Power = 125 kN

Örnekler

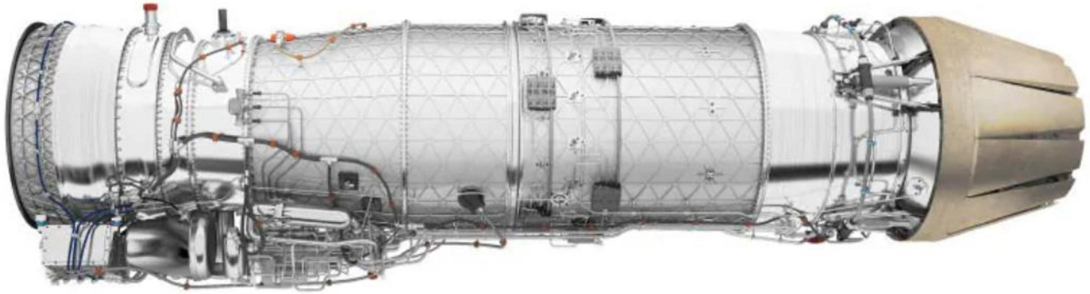
F414 (GE)



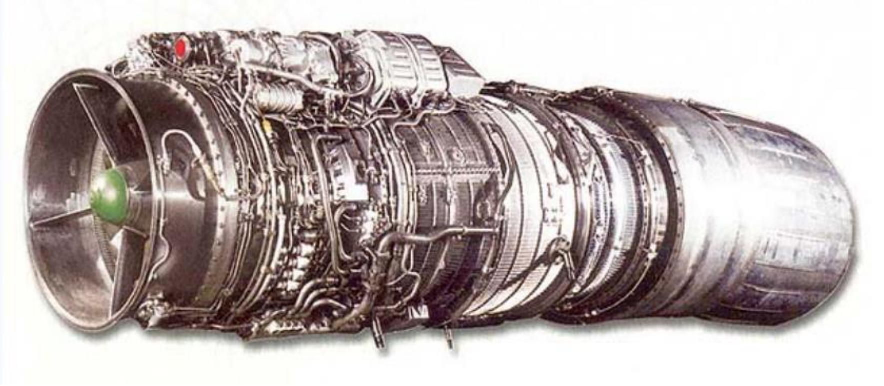
F135 (PW)

TY

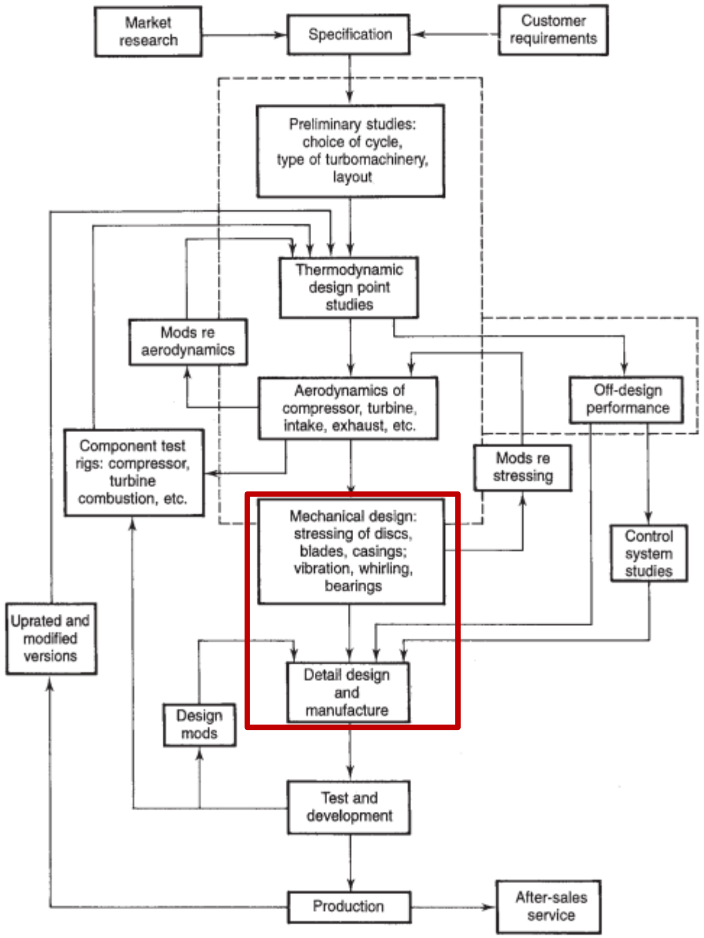
EJ200 (RR)

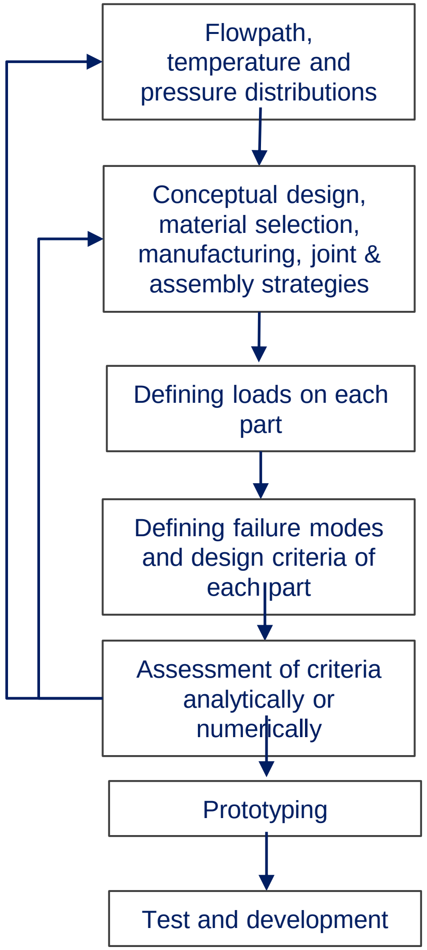


RD33 (Klimov)



Detay Mekanik Tasarım Prosedürü





Flowpath, temperature and pressure distributions

Conceptual design, material selection, manufacturing, joint & assembly strategies

Defining loads on each part

Defining failure modes and design criteria of each part

Assessment of criteria analytically or numerically

Prototyping

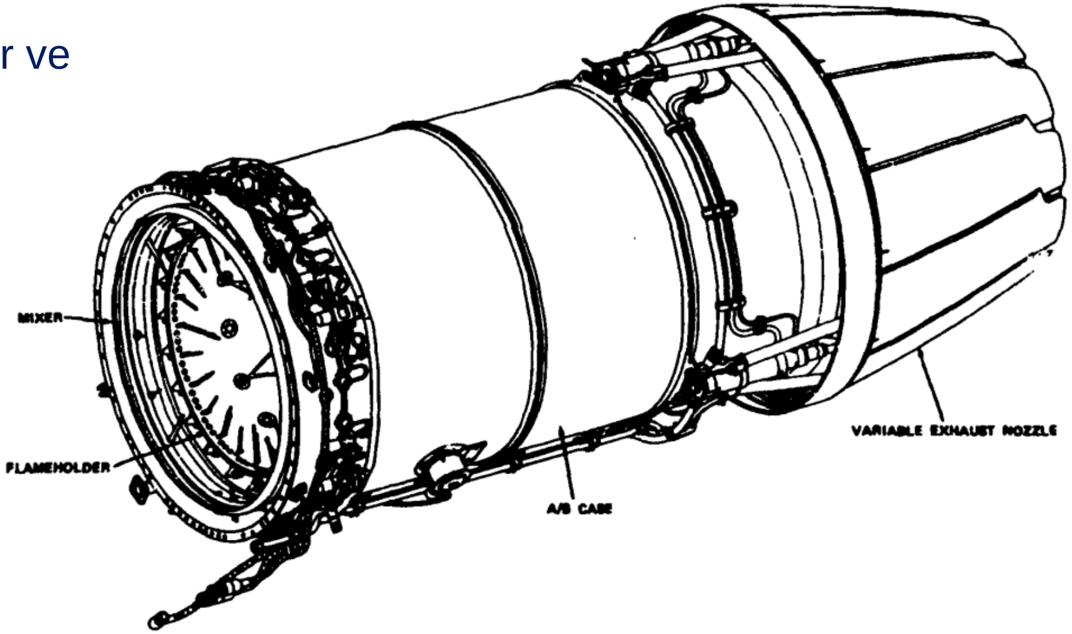
Test and development

Parçalarda görülen yükler

1. Basınç yükleri
2. Termal yükler
   - *Farklı malzeme, farklı termal genleşme katsayıları*
   - *Farklı sıcaklıklardaki parçalar*
   - *Sıcaklık gradyenleri*
3. Mekanik yükler
4. Manevra yükleri
5. Unbalance yükleri

Dış Gömlek (Casing) Tasarımı

- **Fonksiyon:** Ana yapısal parça, mekanik yükleri taşır.
- Bypass hattının akış yolunu oluşturur.
- Diğer statik parçaları taşır (iç gömlek, egzoz nozülü, aksesuarlar ve yakıt hatları, enjektörler, alev tutucular)
- Malzeme seçimi: Düşük çalışma sıcaklıkları, düşük yoğunluklu, yüksek dayanımlı malzemeler (e.g. Titanyum alaşımlar)
- Civatalı bağlantı
- İmalat yöntemi: döküm, talaşlı imalat



Dış Gömlek (Casing) Tasarımı

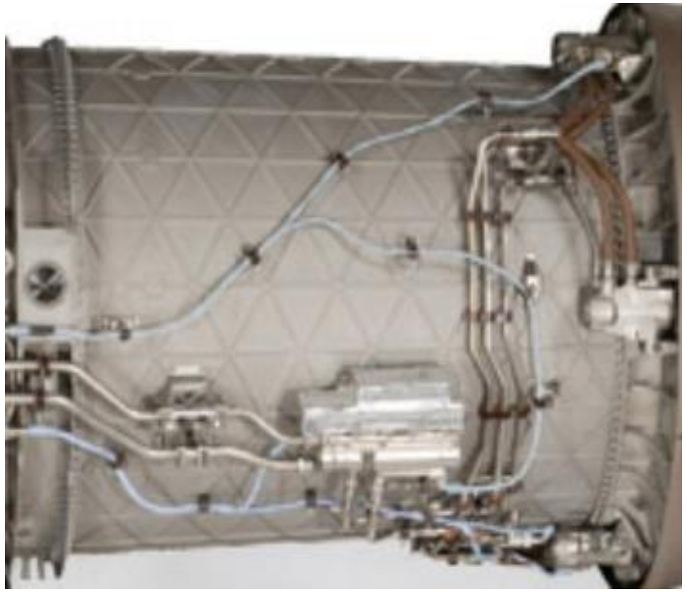
Yükler

- Basınç yükleri
- Manevra yükleri
- Mekanik yüklemeler
- Termal yükler
- Unbalance yükleri

Hata Modları

- Buckling (Burkulma)
- Yield/Rupture
- LCF/Crack Propagation (Çatlak ilerlemesi)
- HCF (Vibration)

F110 Engine Orthogrid Features

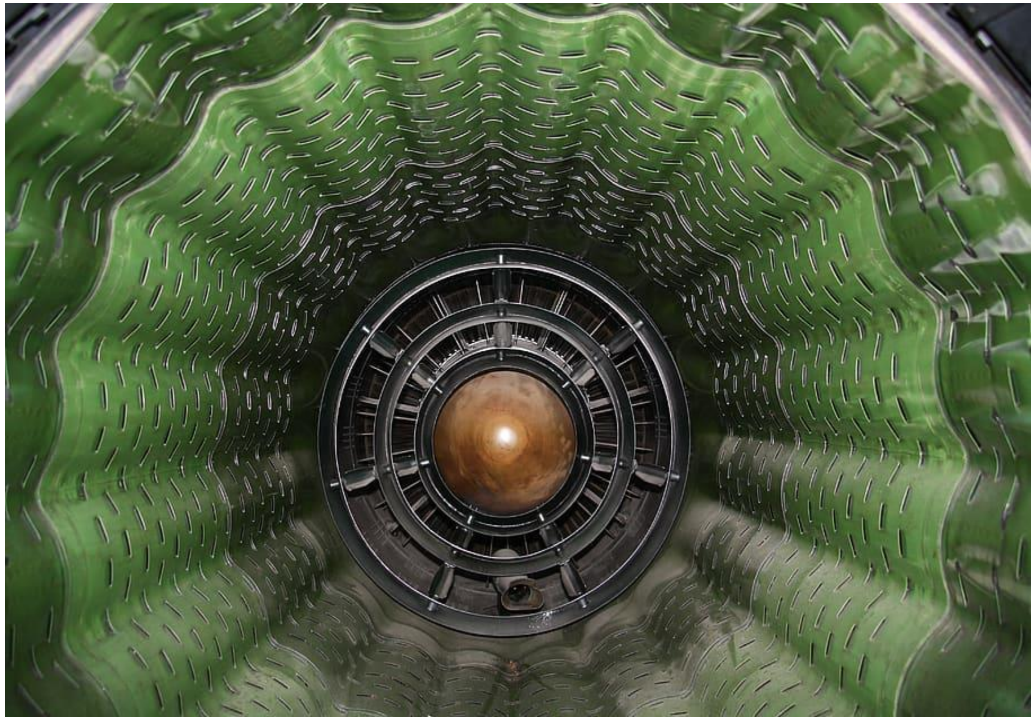


F135 Engine Isogrid Features

İç Gömlek (Liner) Tasarımı

Fonksiyon: Casing parçasının yanma sonucu ortaya çıkan ısıdan etkilenmesini önlemek, ısıl kalkan

- Aero-mekanik parça
- Yük taşıyıcı değil, hafif olması kritik
- Sac malzeme, kalıpla sac şekillendirme
- Soğutma delikleri, delik mesafesi Kt faktörü ve çatlağın yürüyeceği mesafe için önemli
- Montaj & demontaj kolaylığı
- Kaynak & perçin
- Yüksek çalışma sıcaklığı ve oksidasyon: Nikel bazlı süperalaşımlar (e.g. Haynes 188, IN625, Hastelloy X)
- Thermal Bariyer Kaplamalar



J79 İç Gömlek (Afterburner Liner)

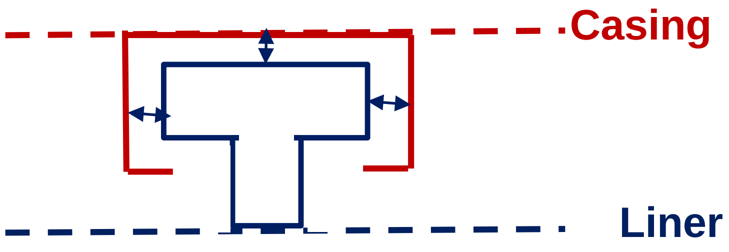
İç Gömlek (Liner) Tasarımı

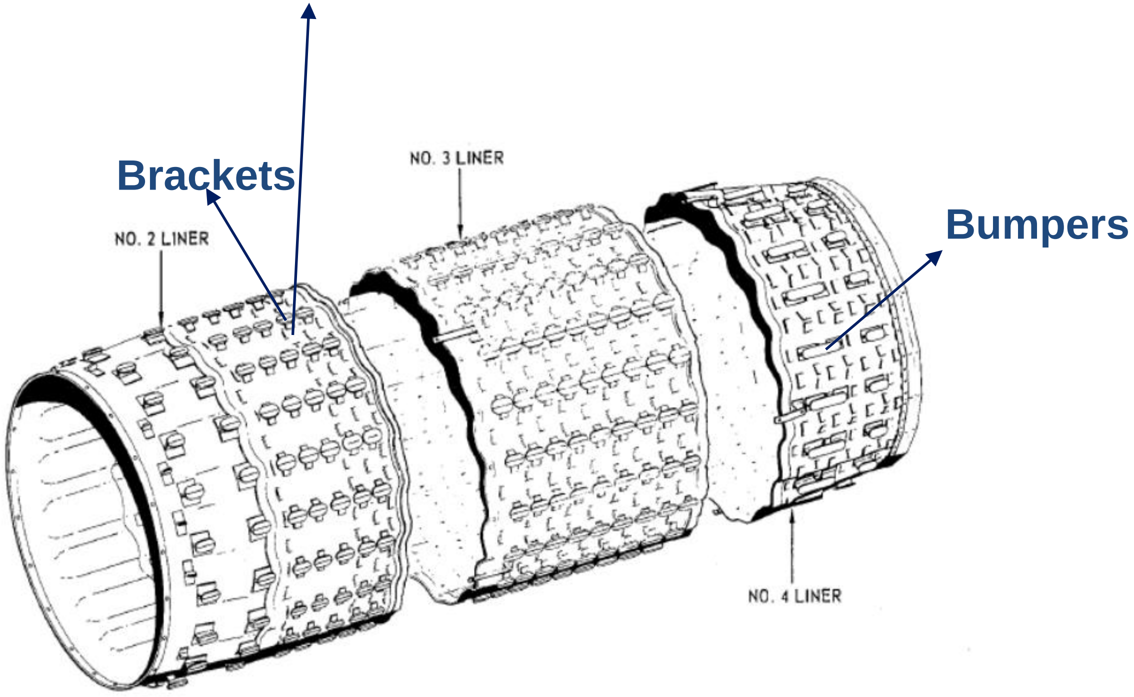
Yükler

- Basınç yükleri
- Manevra yükleri
- Mekanik yükler
- Termal yükler

Hata modları

- Buckling
- Creep
- LCF/Crack Propagation (TMF)
- Yielding/Rupture
- HCF (Vibration)
- Oxidation





Note: Joint strategy plays a significant role in loads distribution and vibration characteristics in this system. After defining connection points, you may evaluate the failure modes by using a simple free body diagram.

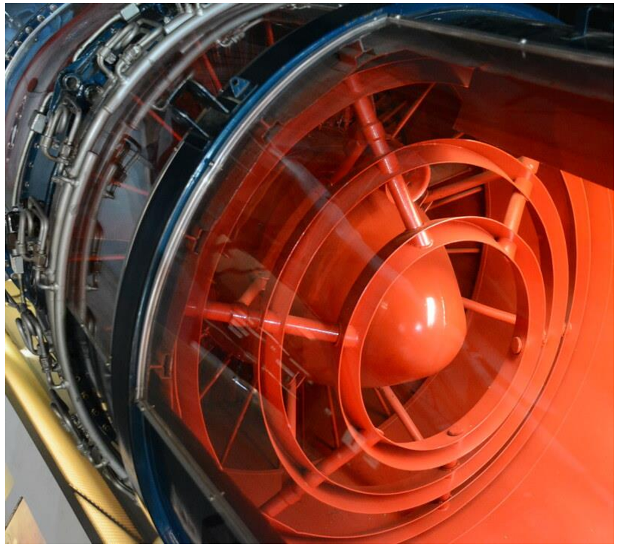
Alev Tutucu (Flame Holder) Tasarımı

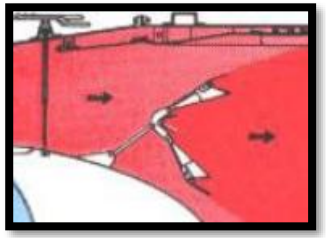
Fonksiyon: Yakıcıya giren havayı yavaşlatıp türbülansa sokarak, alev stabilitesini sağlamak

- Aero-mekanik parça
- AB kapalıyken basınç kaybına neden olur, mümkün olduğunca küçük olmalı
- Bazı statik parçaları taşır (F110 - ignitor)
- Sac malzeme & kaynak
- Bend radyusu
- Yüksek çalışma sıcaklığı ve oksidasyon: Nikel bazlı süperalaşımlar (e.g. Haynes 188, IN625, Hastelloy X)

F414

Radial Flame Holders





J79 Circumferential

(Çevresel) Flame Holders

Alev Tutucu (Flame Holder) Tasarımı

Yükler

- Termal yükler
- Basınç yükleri
- Mekanik yükler

Hata Modları

- Creep
- LCF/Crack Propagation (TMF)
- Yielding/Rupture
- HCF (Vibration)
- Oxidation

F110 Flame Holder

Note: Joint strategy plays a significant role in loads distribution and vibration characteristics in this system. After defining connection points, you may evaluate the failure modes by using a simple free body diagram.

Yakıt Enjektörü (Fuel Injector) Tasarımı

Fonksiyon: Afterburner yakıt ünitesinden gelen yakıtı yanmanın olacağı bölgeye püskürtmek, yakıtın atomizasyonunu sağlamak

- Talaşlı imalat + EDM + Brazing + Kaynak
- Yüksek çalışma sıcaklığı ve oksidasyon: Nikel bazlı süperalaşımlar (e.g Hastelloy X)

Yükler

- Termal yükler
- Basınç yükleri

Hata Modları

- LCF (TMF)
- HCF (Vibration)

F414 Yakıt Enjektörü – Casing Arayüzü

Ateşleyici (Ignitor) Tasarımı

Fonksiyon: Kıvılcım üreterek yakıt-hava karışımında yanmayı başlatmak

Tipleri: Spark plug, torch

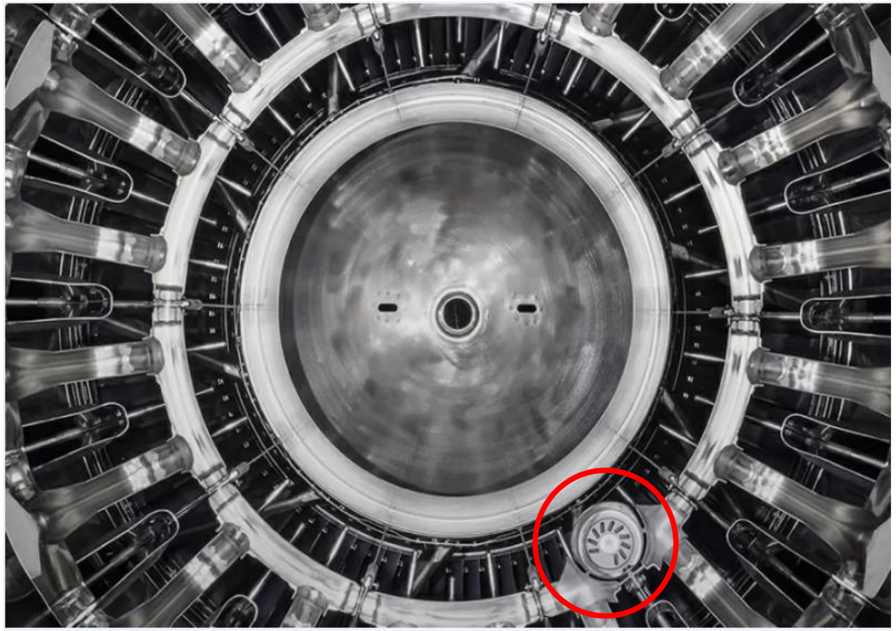
- Yüksek çalışma sıcaklığı ve oksidasyon: Nikel bazlı süperalaşımlar (e.g Hastelloy X, Inconel718)
- Torch sistemi elemanları: Yakıt enjektörü, spark plug, torch housingi
- Flexible arayüz

Yükler

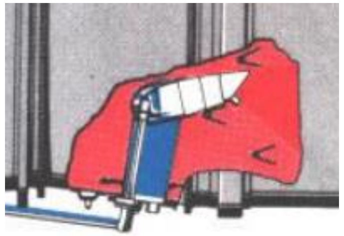
- Termal yükler
- Mekanik yükler

Hata Modları

- LCF/Crack Propagation (TMF)
- HCF (Vibration)

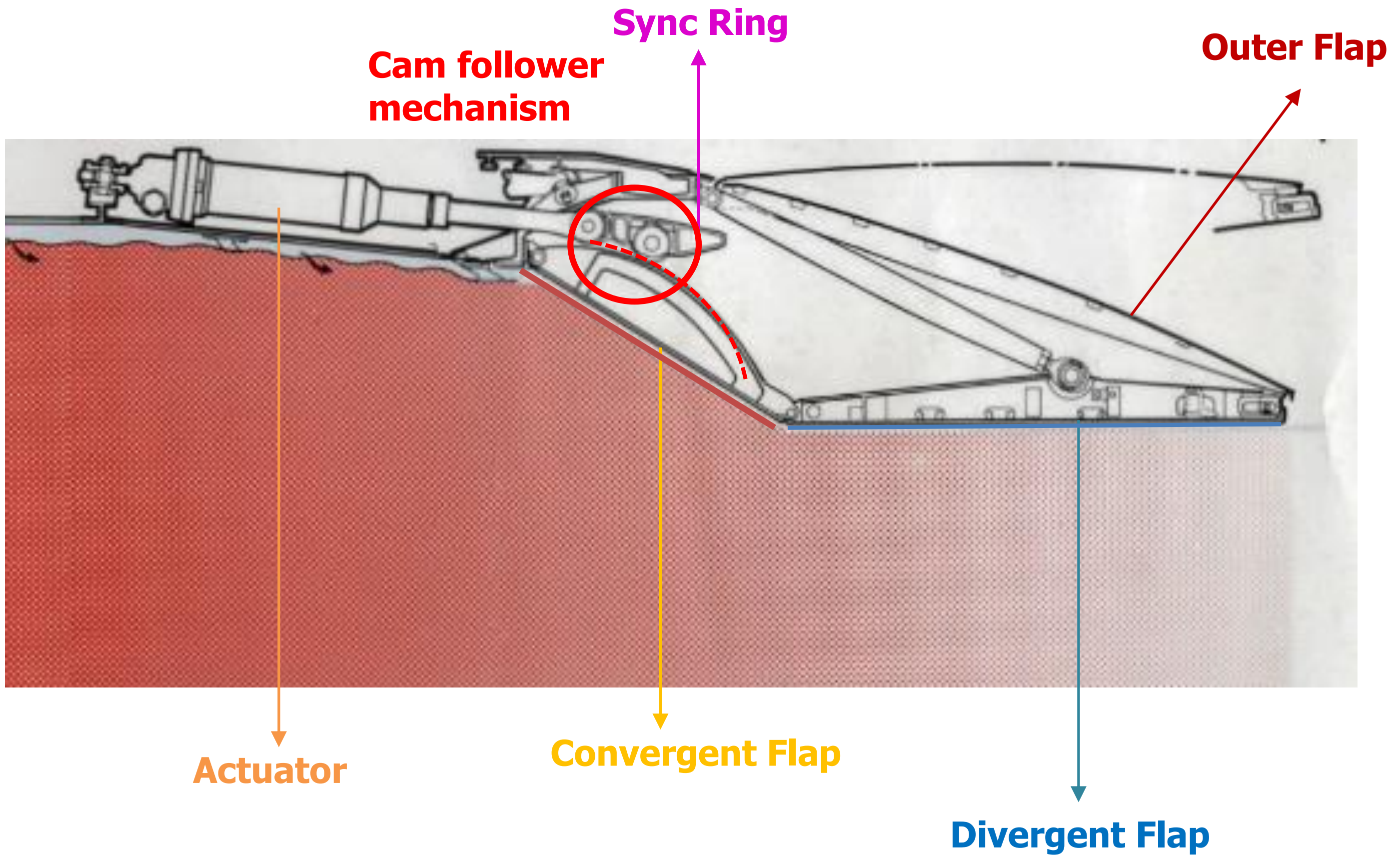


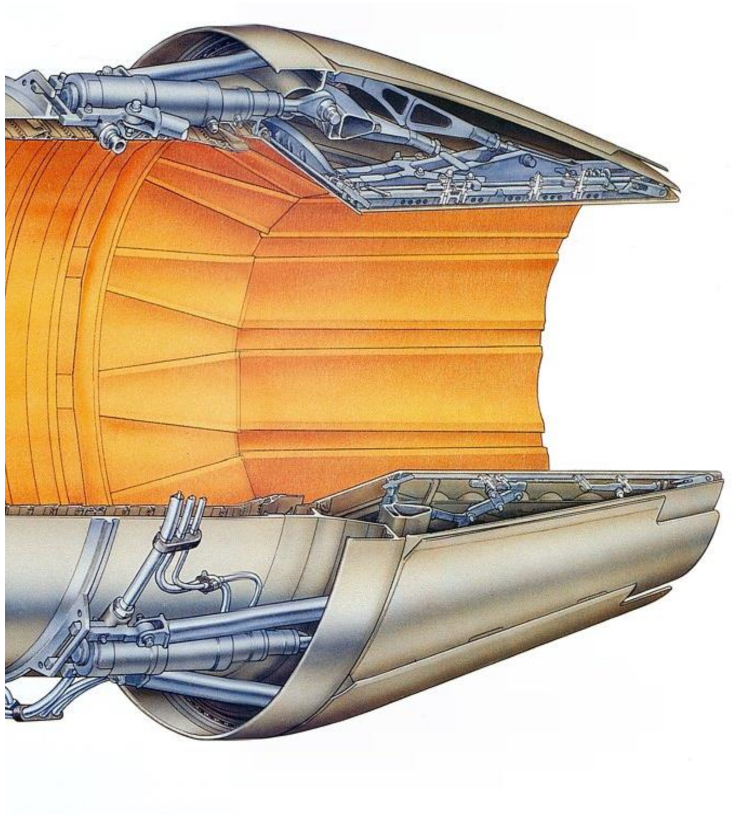
F110 Ignitor



J79 Ignitor

Değişken Nozzle (Variable Exhaust Nozzle) Tasarımı

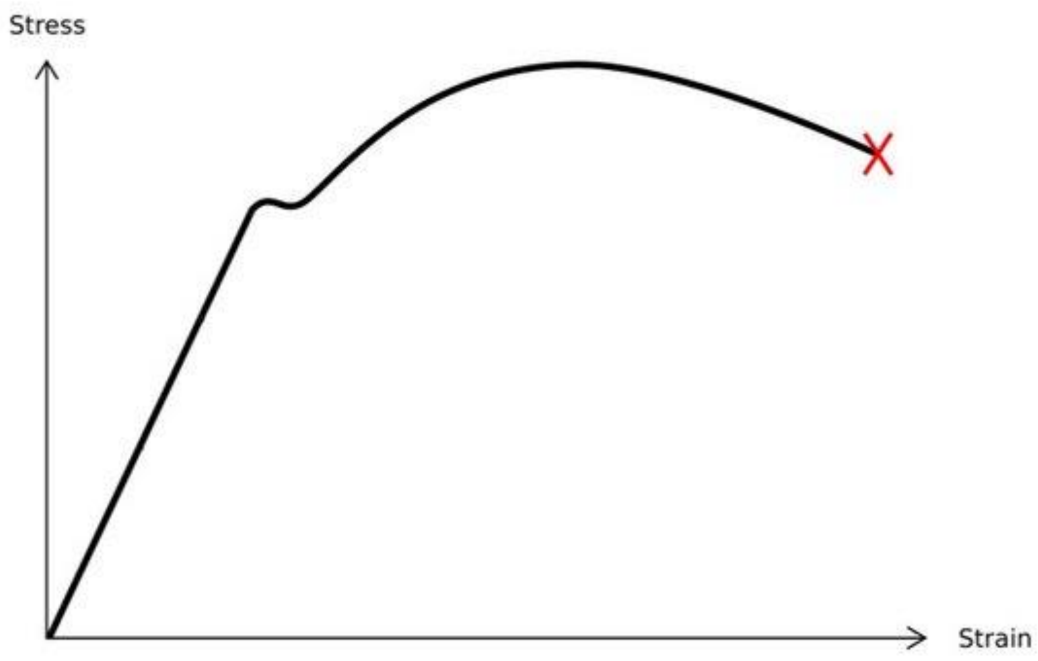


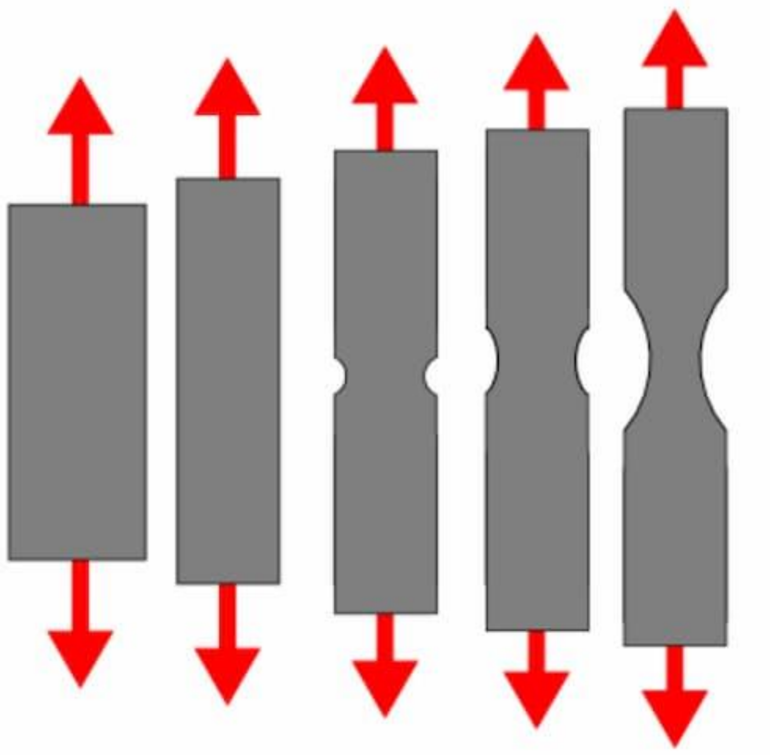


Mekanik Tasarım Kriterleri

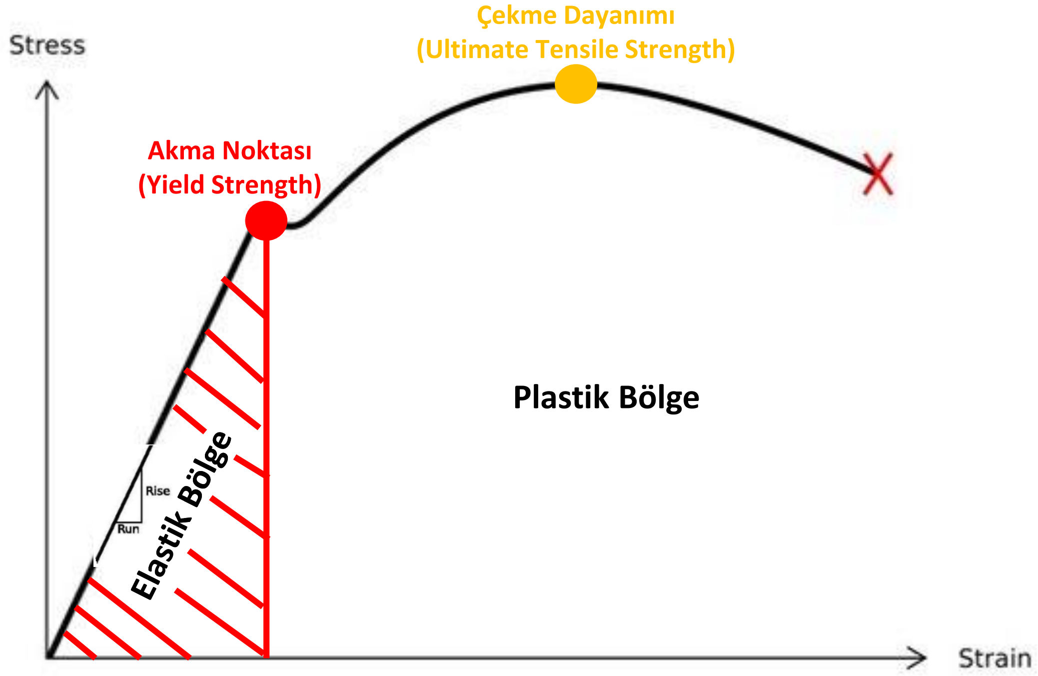
Statik Parçaların Mekanik Tasarım Kriterleri	
Strength (Dayanım)	Parçaların çalışma anında karşılaşabileceği en kötü durumda bütünlüğünü koruması istenmektedir. Bu sebepten akma sınırını (Yield Strength) aşmaması beklenmektedir. Ayrıca bir hata durumunda (Failure) platformun güvenli bir şekilde inmesi sağlanmalıdır bu nedenle çekme dayanımı (Ultimate Tensile Strength) aşılmamalıdır.
Ömür (LCF-HCF)	Parçaların değişken yükler karşısında bütünlüğünü koruması beklenmektedir. Düşük çevrim yorulma (Low Cycle Fatigue) ve Yüksek Çevrim Yorulma (HCF) hesapları yapılmalı ve şartnamede belirtilen ister sağlanmalıdır (İster:25 Saat) (1 çevrim=1 dakika alınmalıdır.)
Overpressure (Yüksek Basınç Durumu)	Motorun çalışması esnasında ikincil akış yolu (bypass flow)) tarafından gelen hava ile ana akış havası (Core flow) basınçları arasındaki farkın bir hata senaryosu sonucunda açılması ve parçaların bu durumda kırıma uğramaması beklenmektedir.
Burkulma (Buckling)	İnce cidarlı parçalar ve basma kuvvetlerine ya da yüksek basınç yüklerine maruz kalan parçalar için kritiktir.
Titreşim (Vibration)	Motorun çalışma aralığında bir doğal frekans istenmemektedir. Çünkü bu durum parçalarda değişken gerilmeler yaratıp yüksek çevrim yorulmasında kırıma götürebilir o yüzden bunlardan kaçınmak gerekmektedir.
Çatlak İlerleme Crack Propagation	Tüm parçalar için kritiktir, Hasar toleransı kapsamında herhangi bir parçada çatlak oluşması durumunda parçanın çatlak ilerleme ömrünün ilk bakım zamanına kadar yetmesi istenir.
Sürünme (Creep)	Yüksek sıcaklığa ve sabit bir yüke maruz kalan parçalarda görülen bir durumdur. Kontrolleri sağlanıp ömür isterini sağlaması beklenir.
Üretilebilirlik	Malzemelerin üretim formlarına ve geometrilerine bakarak bir tasarımın çıkartılması beklenmektedir.
Montaj Edilebilirlik	Montajlama sonunda bir serbestlik dereceleri kısıtlanmış veya serbest bırakılan yerler önceden düşünülerek bırakılmış olmalıdır. Aynı zamanda civata gibi bağlantı elemanlarının montajı için de torklama cihazlarının o bölgeye erişebilmesi beklenmektedir.

Dayanım (Strength)





Dayanım (Strength)



$$\text{Young's Modulus} = \frac{\text{Rise}}{\text{Run}} = \text{Slope}$$

(Elastisite Modülü)

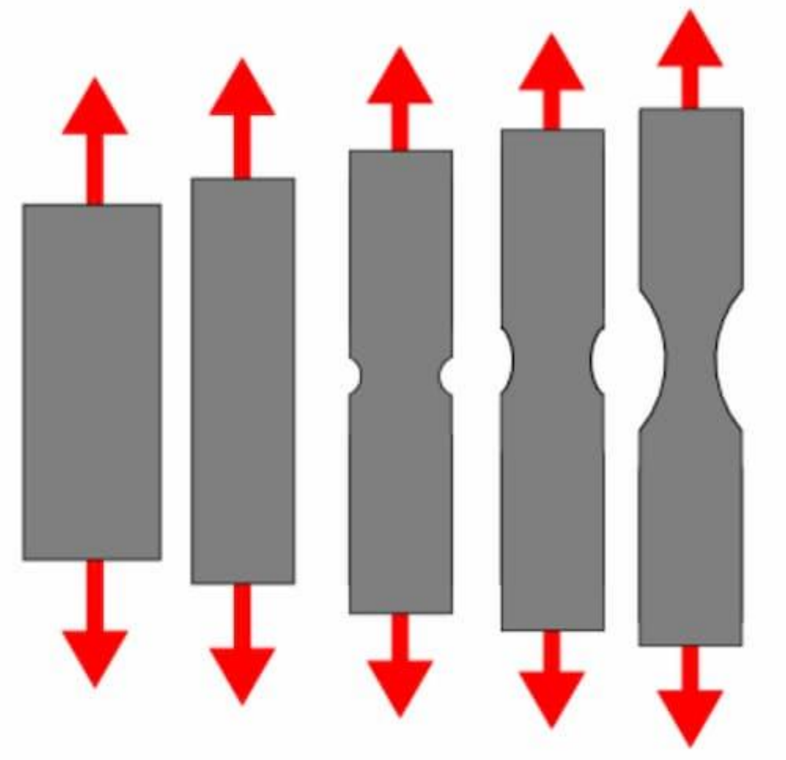
Normal Çalışma Yüklemeleri (Aero,Termal, İkincil Akış, 5G) için:
σ Von-Mises Gerilmesi < σ Akma Gerilmesi

En kötü durum için (Normal Çalışma Yüklemeleri + 7.5G):
σ Von-Mises Gerilmesi < σ Çekme Gerilmesi

NEDEN VON-MISES GERİLMESİ KULLANILMAKTADIR?

Dayanım (Strength)

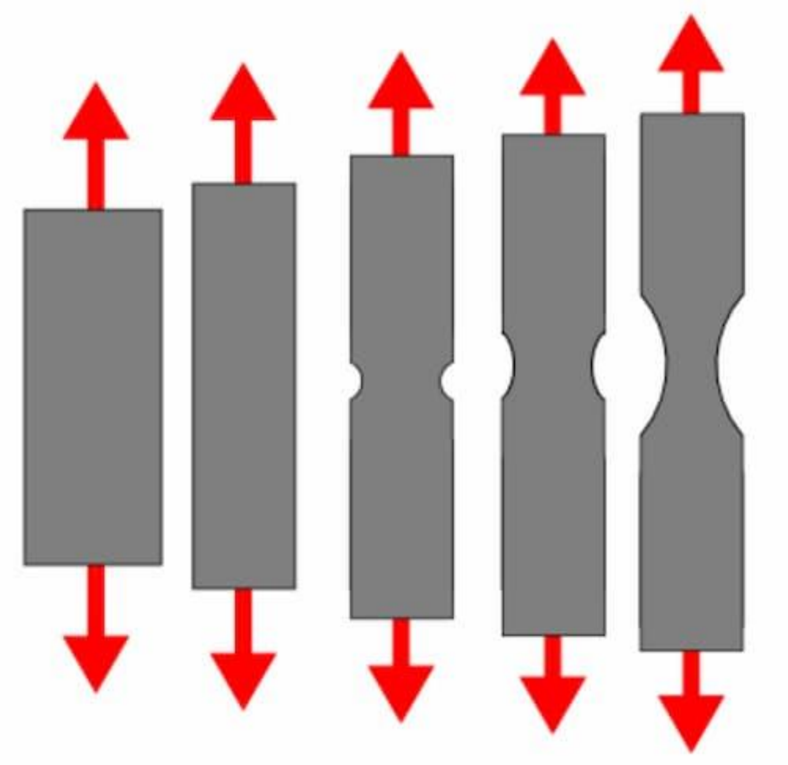
Von-Mises Gerilmesi



Sizce bu parçaya sadece çekme gerilmesi mi etki etmektedir?

Dayanım (Strength)

Von-Mises Gerilmesi

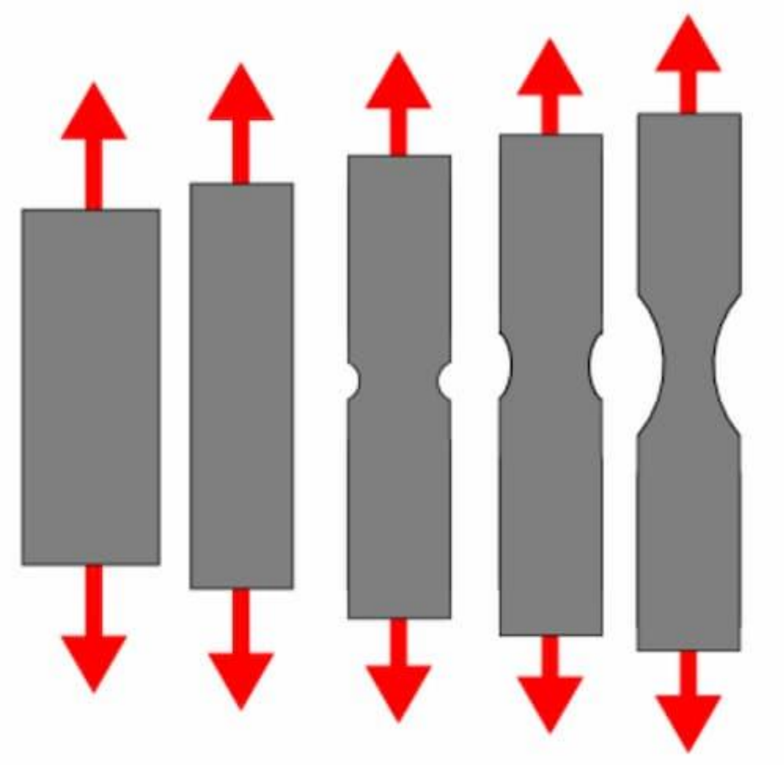


Sizce bu parçaya sadece çekme gerilmesi mi etki etmektedir?

Numunenin x-x yönünde çekildiğini varsayalım. Gerilmenin x-x bileşeni, akma gerilmesinden daha büyük olduğunda malzemenin plastik şekil değiştirmeye başladığını söylemek teknik açıdan doğrudur. Bununla birlikte, gerçek hayatta karşılaşılan uygulamalarda, gerilme tensörleri esas olarak tek eksenli değildir. Gerilme tensörünün tüm bileşenleri çoğu zaman sıfır olmamaktadır.

Dayanım (Strength)

Von-Mises Gerilmesi



- Normal Gerilmeler (σ)
  - Çekme
  - Basma
  - Eğilme
- Kayma Gerilmeleri (τ)
  - Burulma
  - Kesme

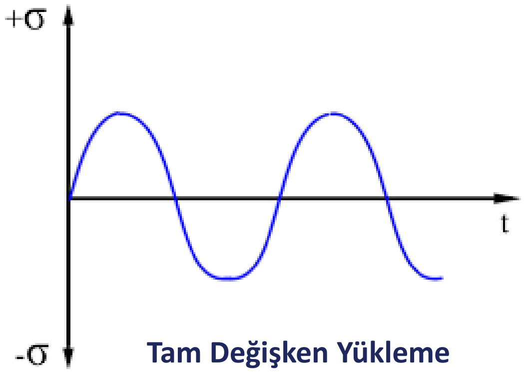
Yukarıda belirtilen gerilmeler temel gerilmelerdir. Parçaların kesitinde bu temel gerilmelerden sadece biri varsa basit gerilme, birkaçı bir arada varsa birleşik gerilme söz konusudur. Statik parçaların neredeyse tamamında birleşik gerilme vardır. Kesitte aynı cinsten gerilmeler söz konusu ise gerilme hesabı gerilmelerin doğrudan toplanması ile yapılır. Kesitte farklı cinsten gerilmeler varsa gerilme hesabı hipotezler ile ilerlemektedir.

$$\sigma_{Mises} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x + 3\tau_{xy}^2 + 3\tau_{yz}^2 + 3\tau_{zx}^2}$$

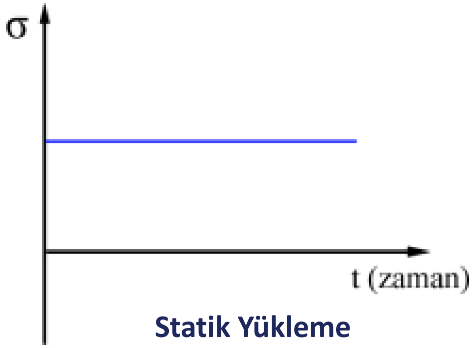
Von-Mises Gerilmesi, normal gerilmeler ile kayma gerilmelerinin bileşkesini bulmak için kullanılan bir yaklaşımdır. Bu sayede tek bir gerilme değerine indirgenebilmektedir.

Ömür (LCF-HCF)

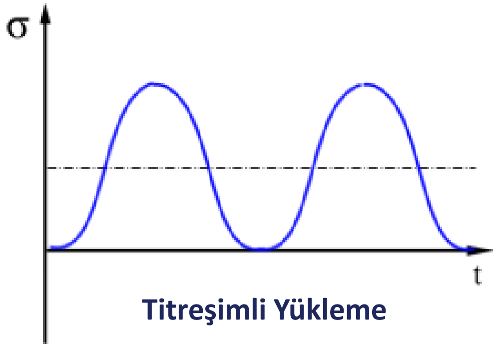
Bir elemana etkiyen kuvvetin değeri kısa zaman aralığında değişiyorsa dinamik yük söz konusudur ve eleman bir süre sonra yorulma sonucu kırılır. Bu nedenle dinamik zorlanmalarda, eleman yalnız şekil değiştirme ve kırılmaya göre değil, yorulmaya göre de değerlendirilmelidir.



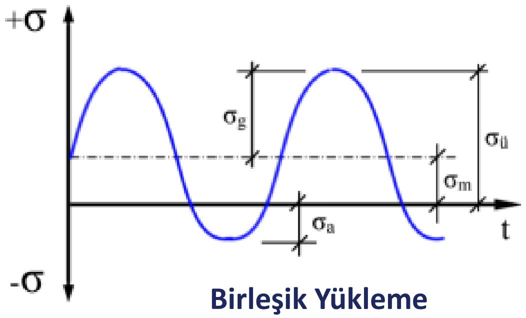
Tam Değişken Yükleme



Statik Yükleme



Titreşimli Yükleme



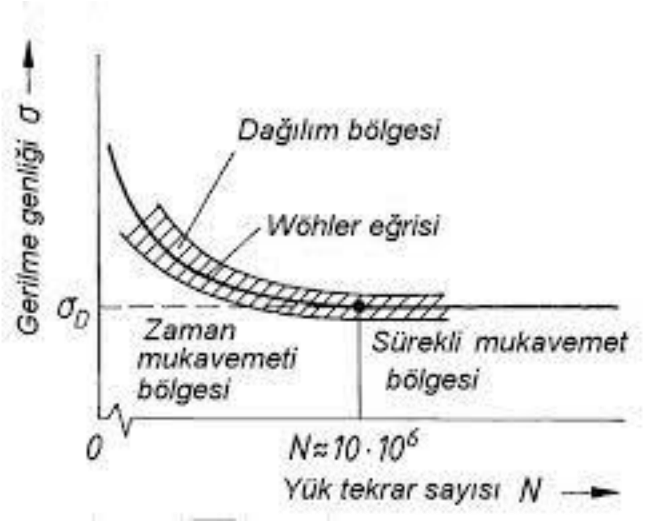
Birleşik Yükleme

Gerilme değişimi aynı zamanda yüklemenin şeklini de karakterize eder. Temel yükleme şekilleri Statik, Titreşimli ve Tam değişken yükleme şeklinde sınıflandırılmıştır. Bu yükler altında oluşan gerilmeler σüst, σalt, σortalama, σgenlik gerilmeleridir. Titreşimli yüklemede alt gerilme sıfırdır, tam değişken yüklemede ise ortalama gerilme sıfırdır.

$$\sigma\text{ortalama(mean)} = \frac{\sigma\text{üst} + \sigma\text{alt}}{2} \qquad \sigma\text{genlik(alternating)} = \frac{\sigma\text{üst} - \sigma\text{alt}}{2}$$

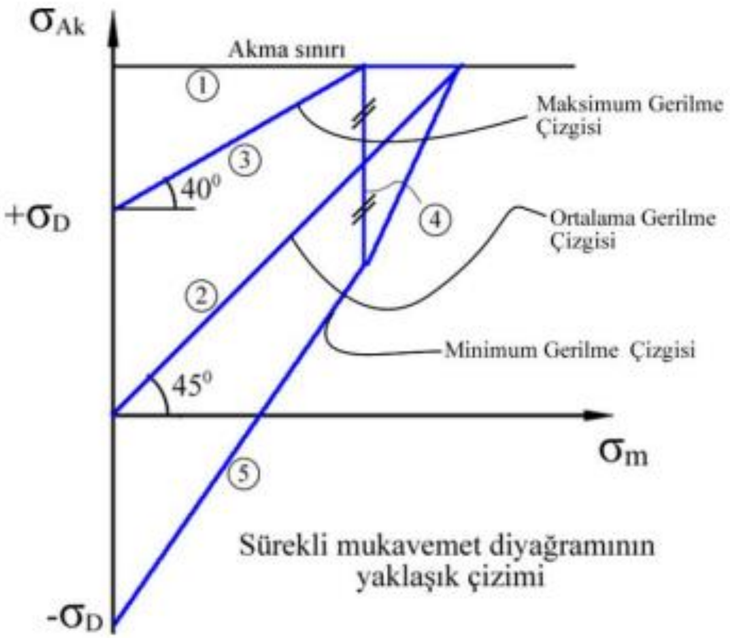
Ömür (LCF-HCF)

Wöhler Eğrisi



Wöhler eğrisi (S-N Curve), gerilme genliği ile yük tekrarı arasındaki bağıntıyı veren eğridir. Belirli bir yük tekrarından sonra malzemenin kırılmasına neden olan gerilmeleri içeren bölgeye zaman mukavemet bölgesi, kırılmanın görülmediği bölgeye sürekli mukavemet bölgesi adı verilir. Her wöhler eğrisi sabir bir ortalama gerilmeye göre oluşabilecek sonuçları vermektedir. Bu nedenle malzemelerin bütün dinamik durumlar için deneylerinin yapılması ve ayrı ayrı Wöhler eğrilerinin çizilmesi gerekir.

Sürekli Mukavemet Diyagramı



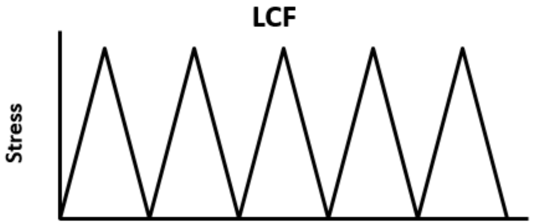
Sürekli mukavemet diyağramının yaklaşık çizimi

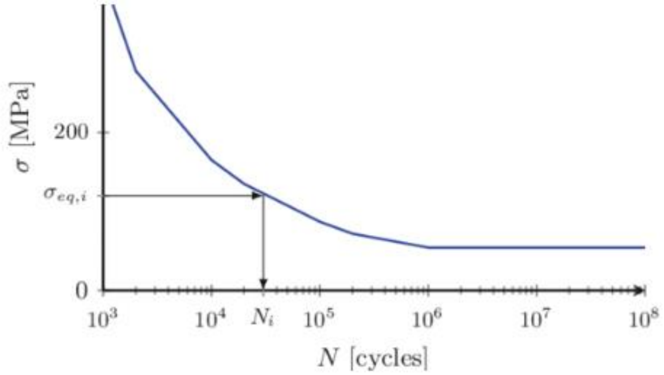
Sizce parçalarımızda sonsuz ömür mü isteriz yoksa öngörebileceğimiz bir ömür mü isteriz?

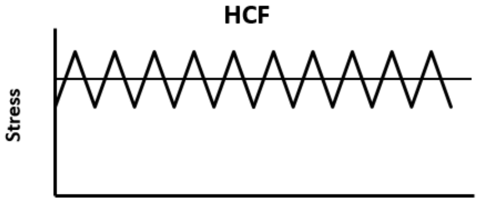
Ömür (LCF-HCF)

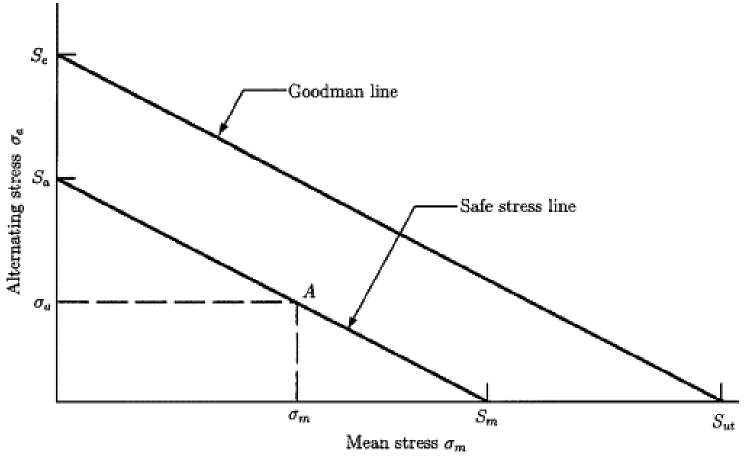
Düşük Çevrimli Yorulma (Low Cycle Fatigue)

Yüksek Çevrimli Yorulma (High Cycle Fatigue)





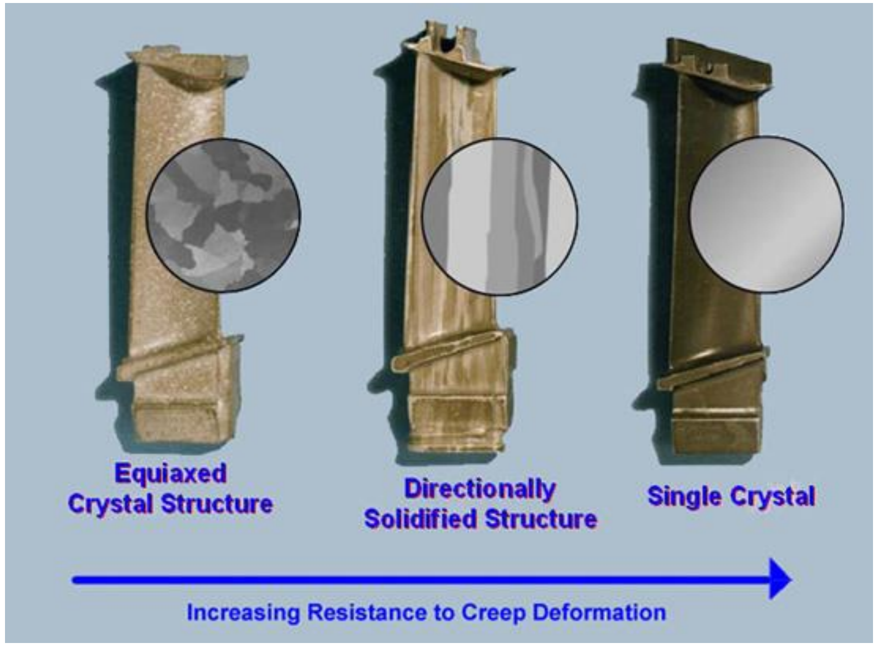




Düşük çevrimli yorulma (Low Cycle Fatigue), yüksek genlikli yorulma hesapları olarak bilinmektedir. Bu motorun çalıştırılmasından çalışma konumuna gelinceye kadar Geçen sürede gerçekleşen gerilme değişimi olarak düşünülebilir. Motor çalışmadığı durumda parçaların üzerinde yük yoktur, çalıştığı anda ise tüm yüklemeler gerçekleşmiştir. Bu değişimde oluşan gerilme genliğinden çalışma sıcaklığına göre çevrim grafiği çıkartılır ve ömür hesabı yapılır. Yapılan hesapta şartanamede verilen ister karşılanmalıdır.

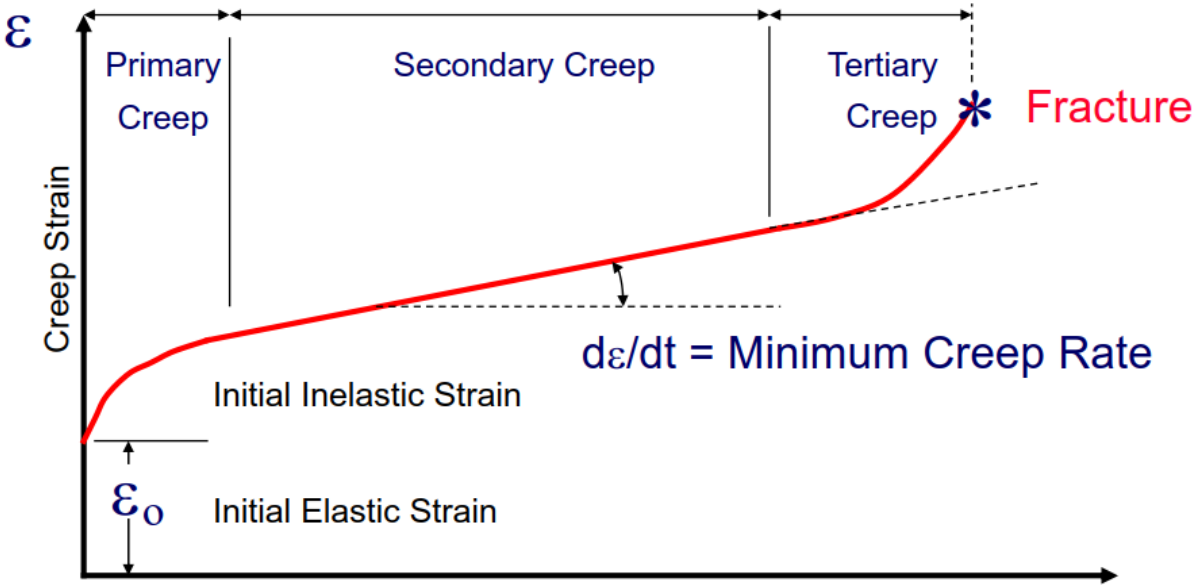
Yüksek çevrimli yorulma (High Cycle Fatigue), düşük genlikli yorulma hesapları olarak bilinmektedir. Bu durum motorun çalışması anında titreşimden veya manevra vb gibi değişken yüklerin oluştuğu durumlarda bakılmalıdır. Bu yorulma tipinde Goodman eğrisi çizilir ve eğrinin altında kalmak hedeflenir.

Sürünme (Creep)

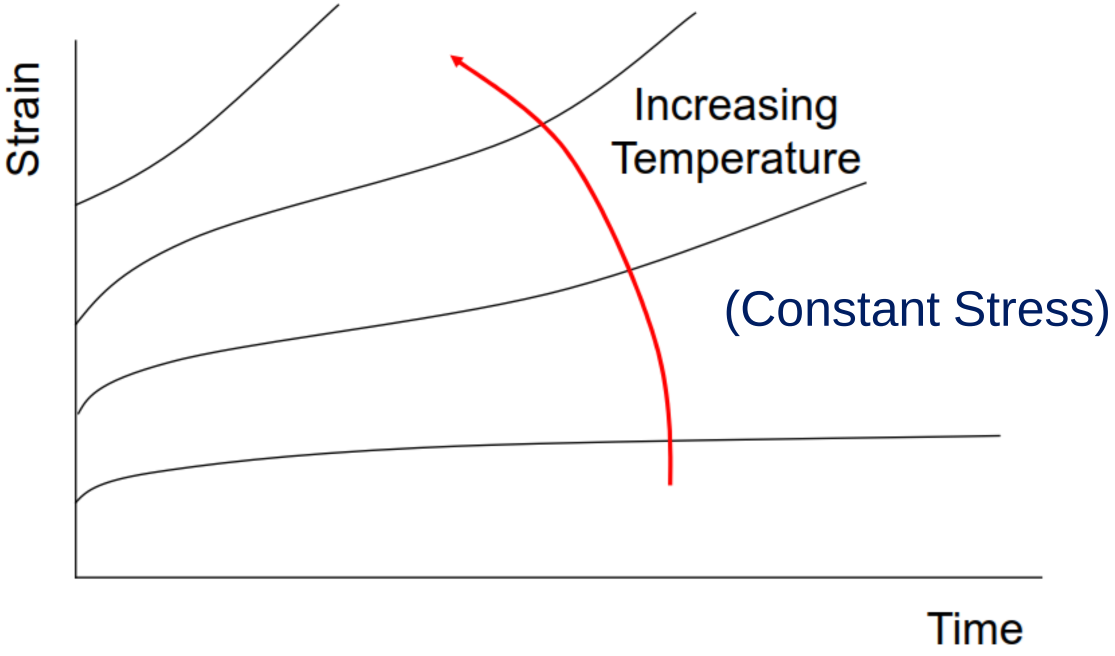


Sıcaklık, atomların hareket yeteneğini arttırdığı için metallerin iç yapılarında difüzyon (yayınma) esaslı mekanizmaların etkin rol oynamasına sebep olmaktadır. Özellikle yüksek sıcaklıklarda atomsal boşluk yoğunluğu da artmaktadır bu sayede dislokasyonların tırmanma ve kayma hareketlerini daha kolay gerçekleştirmelerine neden olur. Ayrıca tane sınırlarının da yol açtığı şekil değişimi metallerin yüksek sıcaklıklarda daha kolay şekil değişimine uğramasının bir başka nedeni olmaktadır. Bu sorunların ışığında yüksek sıcaklıkta ve sabit bir yük altında çalışan parçalarda sürünme (creep) mekanizmasıyla karşılaşılmaktadır. Malzemelerin ergime sıcaklığının yarısından fazla metal sıcaklığı ile karşılaşılırsa bu problem oluşmaktadır.

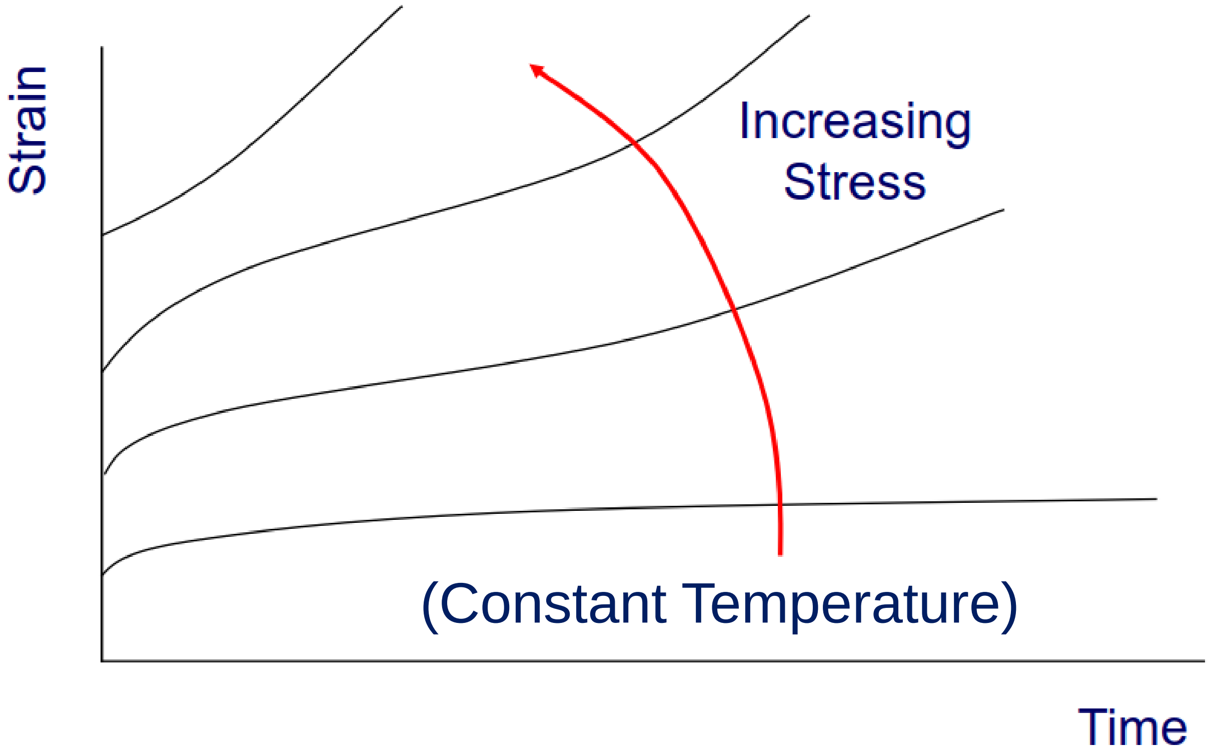
Sürünme (Creep)

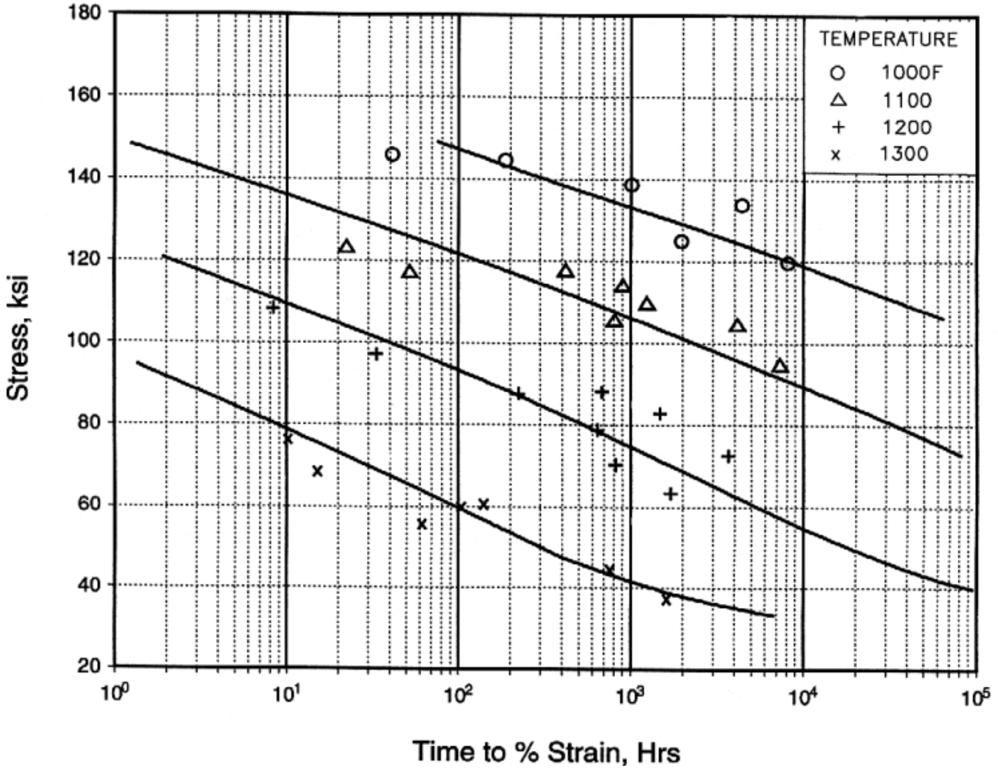


(produced from creep test at constant stress and temperature)



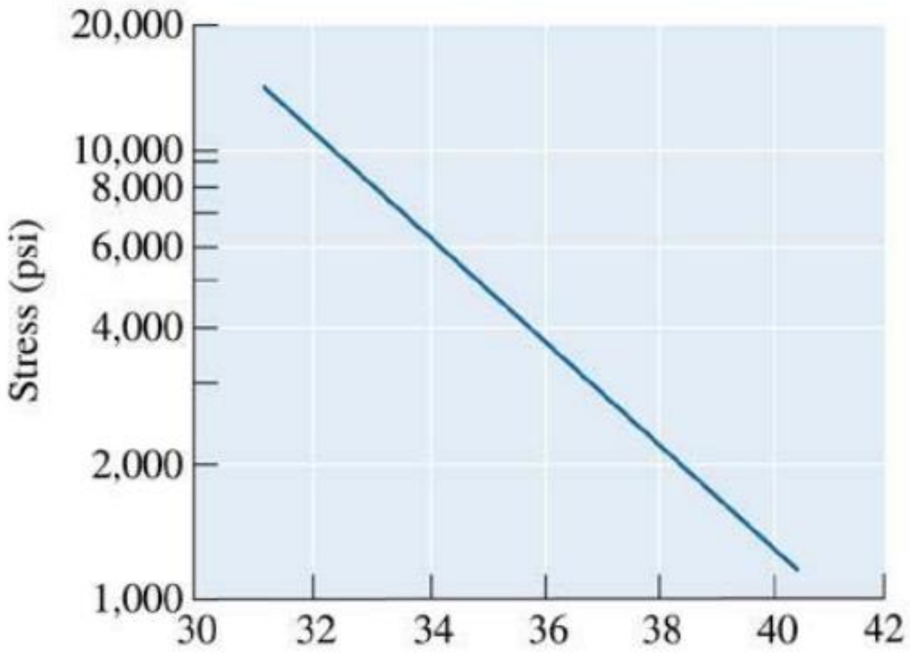
Sürünme (Creep)

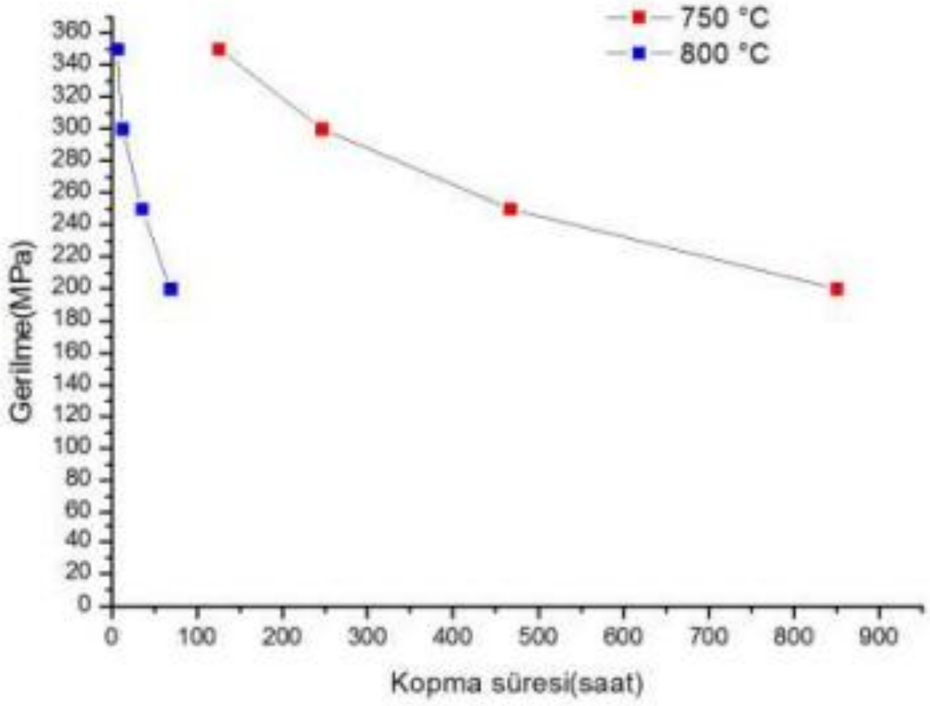




Average isothermal 0.20% creep curves for 718 Alloy forging

Sürünme (Creep)

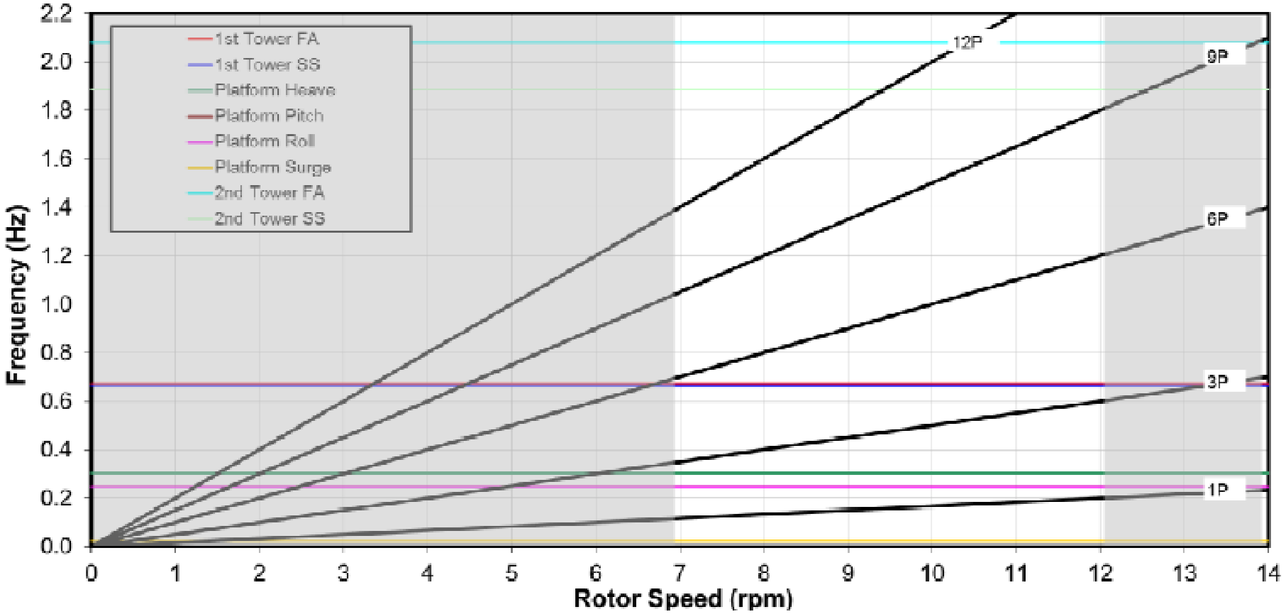


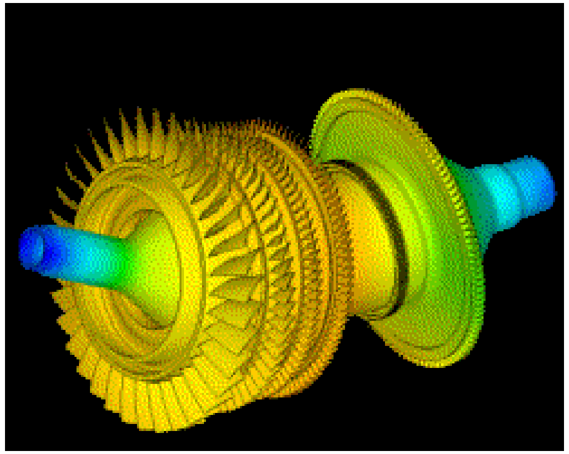


$$\mathrm{LMP} = \underbrace{T}_{\text{Sıcaklık (K)}}(\underbrace{C}_{\text{LMP Sabiti}} + \log \underbrace{t_{\text{kopma}}}_{\text{Kopma Süresi(Saat)}})$$

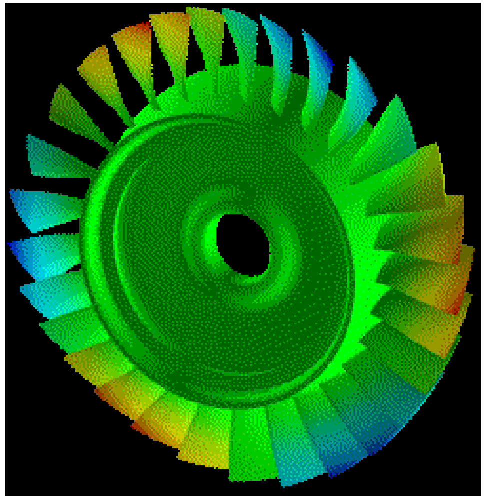
*LMP Sabiti: 15-25 değerleri arasında değişmektedir. Hesaplamalarınızda 20 alabilirsiniz.

Titreşim (Vibration)



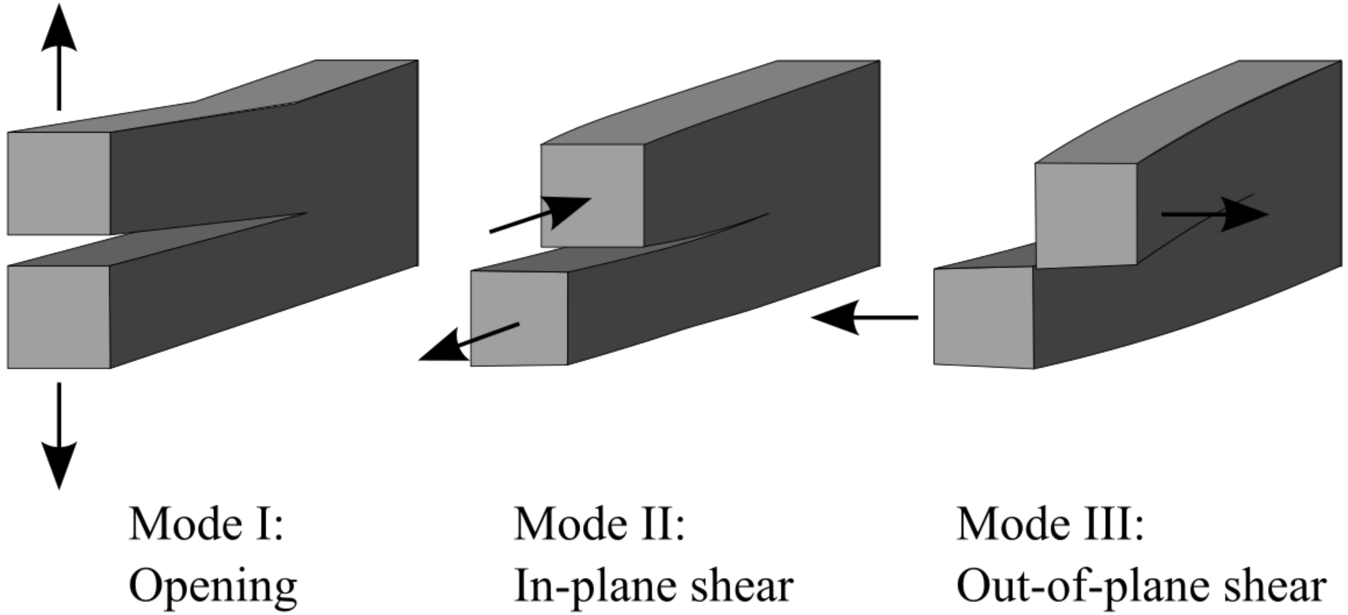


	RPM
Idle	30000
Maximum	90000



- **Tüm parçalar için kritiktir**
- **Modal analiz ile parçanın doğal frekansları belirlenerek parçanın çalışma frekansları dışında kalmasını sağlamak amaçlanır.**
- **Çalışma aralığında parçaların doğal frekansının çakışması durumunda parçalar üzerinde değişken gerilme (alternating stress) olacaktır, bu durumda da parçada HCF riski bulunmaktadır. Bu sebepten çakışmalardan kaçılmaya çalışılmalı. Eğer olmuyorsa bununla yaşamanın çaresine bakılmalıdır.**

Çatlak İlerleme (Crack Propogation)



- **Tüm parçalar için kritiktir,**
- **En sık görülen yükleme şekli Mode 1'dir.**
- **Hasar toleransı kapsamında herhangi bir parçada çatlak oluşması durumunda parçanın çatlak ilerleme ömrünün ilk bakım zamanına kadar yetmesi istenir.**
- **Mode 1 şekil itibariyle çekme gerilmesi altında çatlak ilerlemeye çalışır yani basma kuvveti altında çatlak ilerlemesinden endişe edilmemelidir.**

Çatlak İlerleme (Crack Propogation)

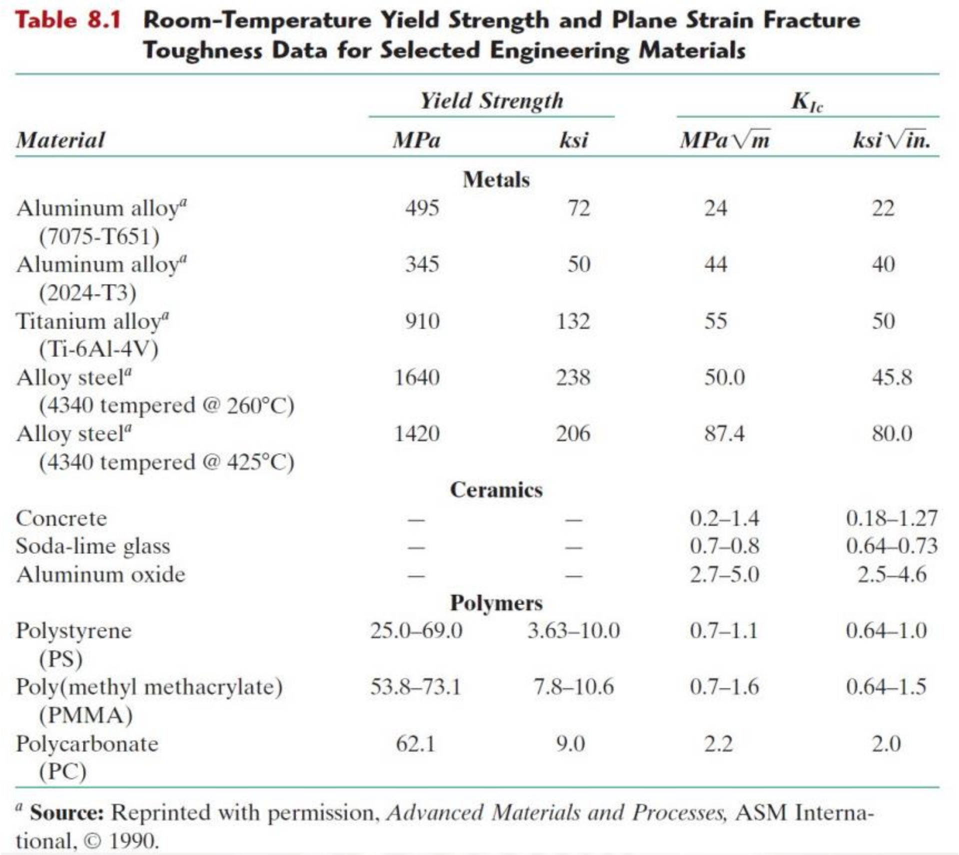
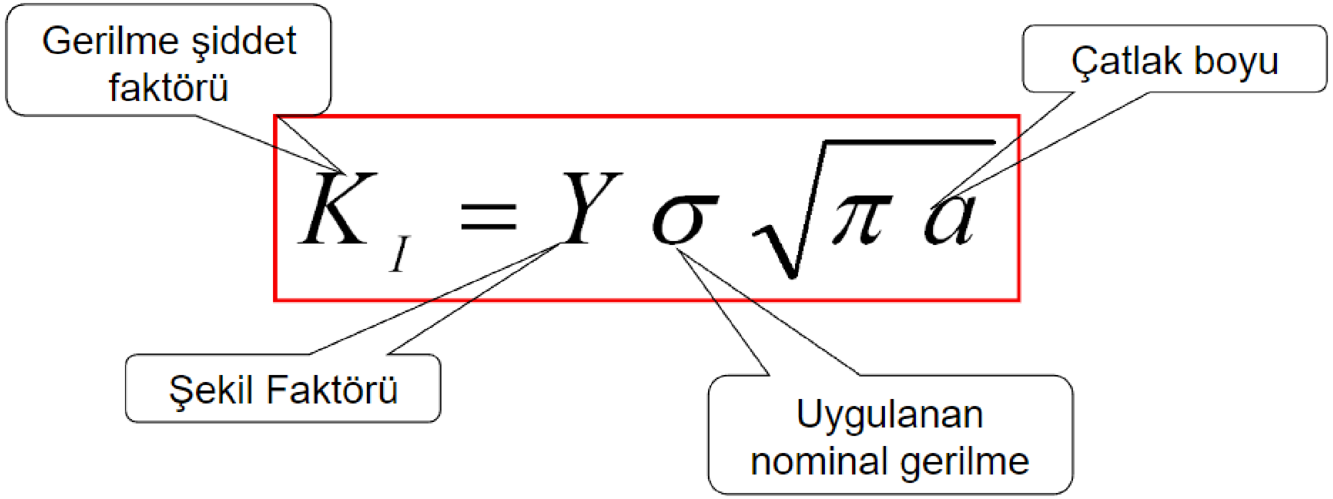


Table 8.1 **Room-Temperature Yield Strength and Plane Strain Fracture Toughness Data for Selected Engineering Materials**

	Yield Strength		K_{Ic}	
Material	*MPa*	*ksi*	$MPa\sqrt{m}$	$ksi\sqrt{in.}$
Metals				
Aluminum alloy[a] (7075-T651)	495	72	24	22
Aluminum alloy[a] (2024-T3)	345	50	44	40
Titanium alloy[a] (Ti-6Al-4V)	910	132	55	50
Alloy steel[a] (4340 tempered @ 260°C)	1640	238	50.0	45.8
Alloy steel[a] (4340 tempered @ 425°C)	1420	206	87.4	80.0
Ceramics				
Concrete	—	—	0.2–1.4	0.18–1.27
Soda-lime glass	—	—	0.7–0.8	0.64–0.73
Aluminum oxide	—	—	2.7–5.0	2.5–4.6
Polymers				
Polystyrene (PS)	25.0–69.0	3.63–10.0	0.7–1.1	0.64–1.0
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	0.7–1.6	0.64–1.5
Polycarbonate (PC)	62.1	9.0	2.2	2.0

[a] **Source:** Reprinted with permission, *Advanced Materials and Processes,* ASM International, © 1990.



$$K_I = Y \sigma \sqrt{\pi a}$$

Gerilme şiddet faktörü

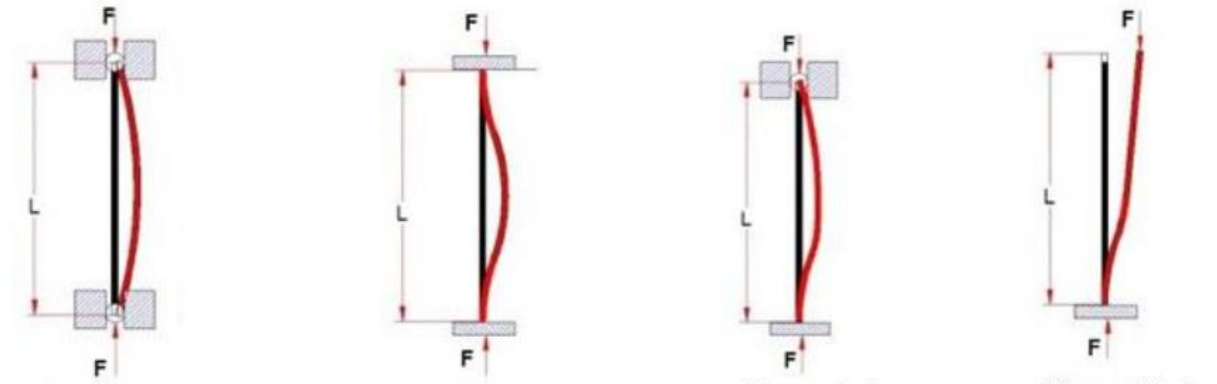
Çatlak boyu

Şekil Faktörü

Uygulanan nominal gerilme

- **KI < KIc ise çatlak ilerlemez.**
- **KI>Kic ise çatlak hızla ilerler ve Gevrek kırılma meydana gelir.**
- **Y değeri 1.1 alınabilir.**

Burkulma (Buckling)



Her iki uç mafsallı
K=1

Her iki uç sabit
K=0.25

Bir uç mafsallı
Bir uç sabit
K=0.5

Bir uç serbest
Bir uç sabit
K=4

$$F_{cr} = \frac{\pi^2 * E * I}{L^2} \qquad F_{cr} = \frac{\pi^2 * E * I}{0.25 * L^2} \qquad F_{cr} = \frac{\pi^2 * E * I}{0.5 * L^2} \qquad F_{cr} = \frac{\pi^2 * E * I}{4 * L^2}$$

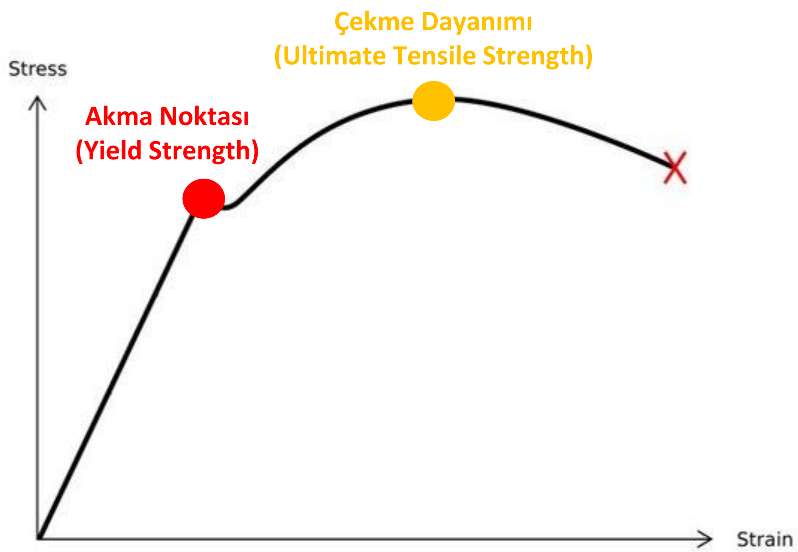
Hesaplamak için 3 metod vardır:

1. **Bruhn Teori**
2. **Eigenbuckling Analiz**
3. **Nonlinear Buckling Analiz**

Bu hesaplamalarda “Slenderness ratio” bakılmalı, 120’den düşük ise 1 ve 2. metod için emniyet katsayısı 5 alınmalıdır. 120’den büyük ise emniyet katsayısına gerek yoktur. 3. Metod için emniyet katsayısı hiçbir durumda yoktur.

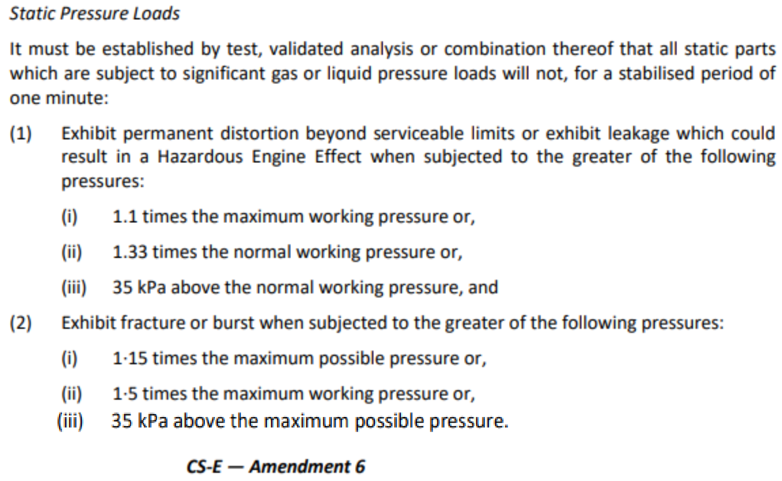
- **İnce cidarlı parçalar, basma kuvvetlerine ya da yüksek basınç yüklerine maruz kalan parçalar içi kritiktir.**
- **Mekanik veya yapısal bir eleman eksenel olarak basma kuvveti altında iken, kuvvet belli bir kritik büyüklüğe ulaşınca eleman ani bir deformasyona uğrar. Bu fenomen burkulma (Buckling) olarak adlandırılır.**
- **Kritik yük büyüklüğü (Fcr);**
  - **-Mekanik elemanın yapıldığı malzemeye,**
  - **-Geometrik ölçülerine,**
  - **-Mafsal durumuna göre değişir.**

Yüksek Basınç Durumu (Overpressure)



Maksimum Çalışma Basıncı altında beklenen dayanım isteri:
σ Von-Mises Gerilmesi < σ Akma Gerilmesi

Hata Durumu Basıncı altında beklenen dayanım isteri:
σ Von-Mises Gerilmesi < σ Çekme Gerilmesi



Static Pressure Loads

It must be established by test, validated analysis or combination thereof that all static parts which are subject to significant gas or liquid pressure loads will not, for a stabilised period of one minute:

(1) Exhibit permanent distortion beyond serviceable limits or exhibit leakage which could result in a Hazardous Engine Effect when subjected to the greater of the following pressures:
- (i) 1.1 times the maximum working pressure or,
- (ii) 1.33 times the normal working pressure or,
- (iii) 35 kPa above the normal working pressure, and

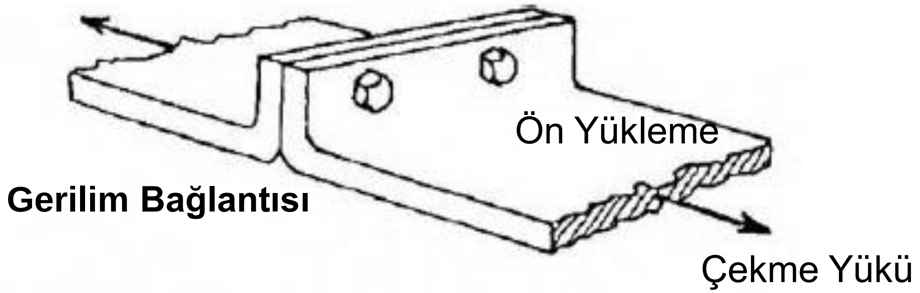
(2) Exhibit fracture or burst when subjected to the greater of the following pressures:
- (i) 1·15 times the maximum possible pressure or,
- (ii) 1·5 times the maximum working pressure or,
- (iii) 35 kPa above the maximum possible pressure.

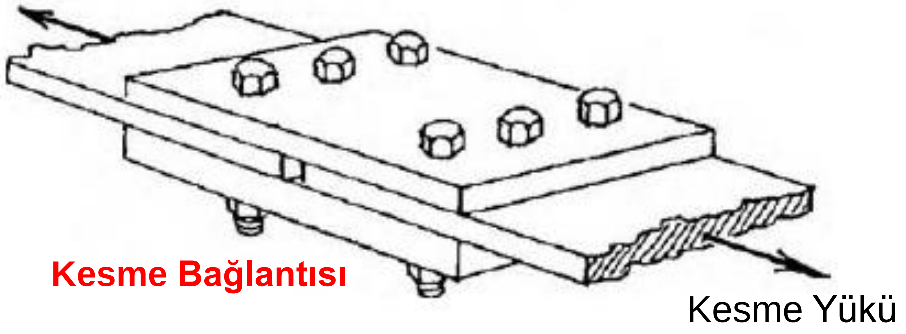
CS-E — Amendment 6

Motorun çalışması esnasında ikincil akış yolu (bypass flow)) tarafından gelen hava ile ana akış havası (Core flow) basınçları arasındaki farkın bir hata senaryosu sonucunda açılması ve parçaların bu durumda kırıma uğramaması beklenmektedir. Burada 3 tip basınç vardır;
-Normal Çalışma Basıncı: Çevrimde normal şartlar altında karşılaşılan basınç değeridir.
-Maksimum Çalışma Basıncı: Motorun en zorlandığı durumda meydana gelen basınç değeridir.
-Hata Durumu Basıncı: Motorun çalışması esnasında oluşabilecek bir hata sonucunda oluşan basınçtır.

Civatalı Bağlantı Tasarımı

2 ya da daha fazla bağlantı elemanının –flanş-, bağlama elemanları -cıvata ya da somun- üzerine önyükleme uygulanarak birbirine mekanik olarak birleştilmesi ile oluşturulan bağlantılara "civatalı bağlantı" denmektedir. Bağlantıya etkiyen yükleme koşullarına göre 2 tip civatalı bağlantıdan bahsedilebilir;



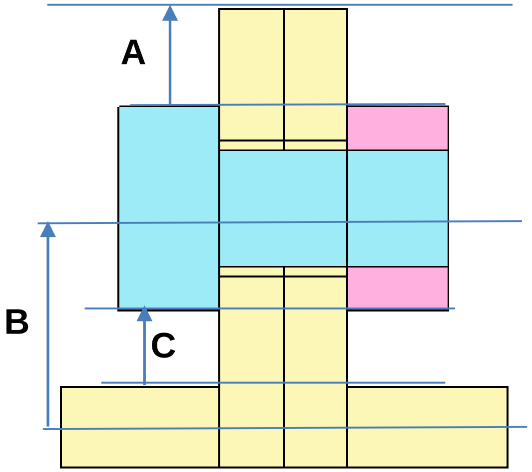


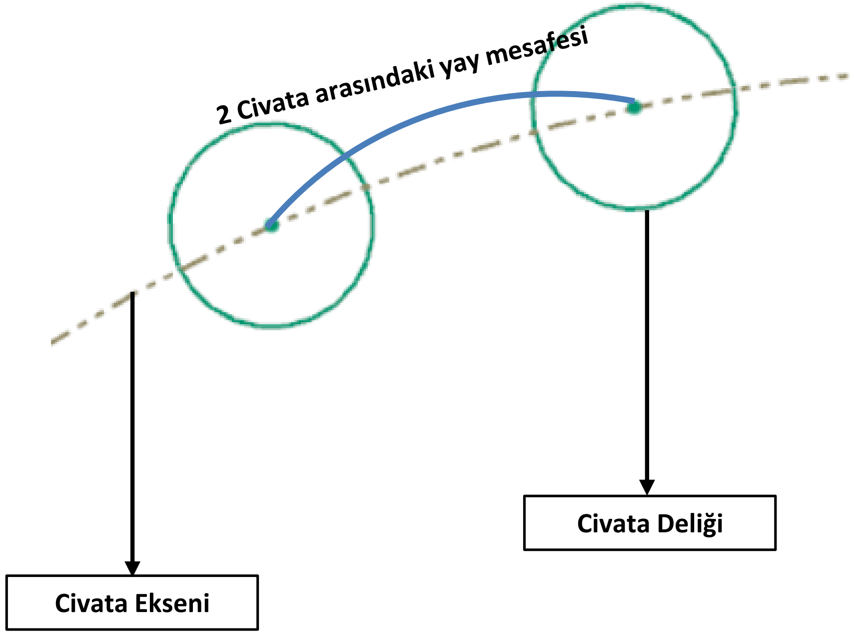
1. Gerilim Bağlantısı; Bağlantı üzerindeki kuvvetlerin etki çizgisi cıvatanın eksenlerine paralel ise, bağlantının gerilim yüklü olduğu söylenir ve buna gerilim veya çekme bağlantısı denir.

2. Kesme Bağlantısı; Bağlantı üzerindeki kuvvetlerin etki çizgisi cıvatanın eksenlerine dik ise, bağlantının kesme yüklü olduğu söylenir ve buna kesme veya kesme bağlantısı denir.

- Kesme Civataları
- Perçin
- Pim

Civatalı Bağlantı Tasarımı





-Moment kolu oluşturup parça üzerinde ek yüklemelerde kaçınmak için B ölçüsü olabildiğince küçük seçilmelidir.
-A değeri arttıkça ağırlık artmaktadır.
-C değeri montaj araçlarının erişebileceği şekilde seçilmelidir.

Civata Sayısı Belirlenirken;

$$\text{Civata Oranı} = \frac{\text{2 Civata Arasındaki Yay Mesafesi}}{\text{Delik Çapı}}$$

Bu oran 5'ten küçük, montaj edilebilirlik açısından 2'den büyük olmalıdır.

Detay Tasarım Raporu İçin Tavsiyeler

- Present 3D view at the beginning with part names
- Define all interfaces, including joint and sealing elements (Do not forget interface with core engine)
- Show assembly sequence, check tool accessibility
- Check benchmarks. You can take some ideas
- Tables and graphs make reading easier
  - Material names on graph with arrows
  - Metal temperatures plots
  - Secondary air system flows
  - Pressure map plots
  - Stress plots
  - Criteria table
  - Summary table (of results, with brief comments)

TUSAŞ MOTOR SANAYİİ A.Ş.
TUSAŞ ENGINE INDUSTRIES, INC.

TEŞEKKÜR EDERİZ

TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Yapısal Analiz Teknik Eğitim

10.01.2023

İçerik ve Amaç

İçerik:

- Tanıtım
- Motorlarda yapısal analiz türleri
- Sonlu elemanlar yöntemi ve adımları
- Art Yakıcı Üzerine Gelen Temel Yapısal Yükler
- Mukavemet, manevra, modal, dinamik, yorulma ve sürünme hesapları
- Uygulama
- Soru&Cevap

Amaç:

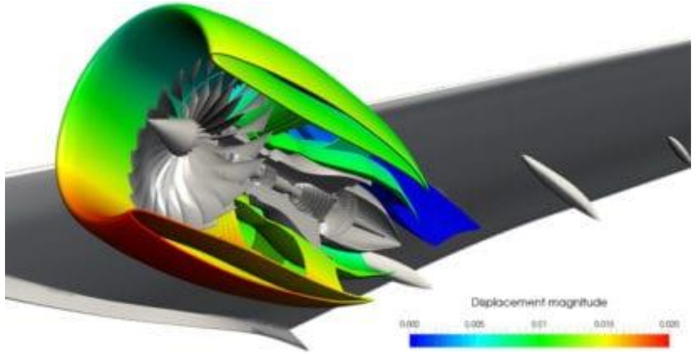
- Yapısal analiz türlerini tanımak
- Art yakıcı üzerine gelen temel yapısal yükleri anlamak
- Mukavemet, manevra, yorulma, sürünme, modal hesaplarını ve analizlerini yapmak

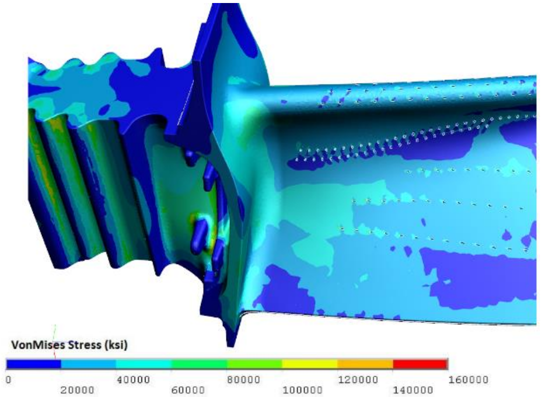
Eğitim süresi ➔ 2 saat

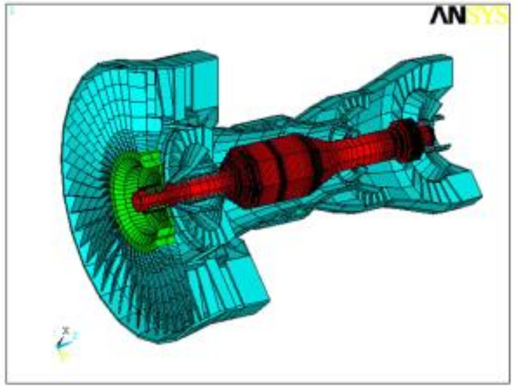
Motorlarda Yapısal Analiz Türleri

- **Doğrusal Elastik Analiz**
- Doğrusal Olmayan Elastoplastik analiz
- Termal Mekanik Analiz
- Burkulma Analizleri
- **Modal Analiz**
- Harmonik (Frekans Cevap Analizleri)
- Zamana bağlı analizler
- Doğal zorlanım, serbest titreşim, spektrum analizleri
- Darbe analizleri (Kuş Çarpması)
- Yapısal Optimizasyon

- **Ömür Analizleri**
- **Sürünme Analizleri**
- Akustik Analizler
- Çatlak ilerleme ve kırılma/kopma analizleri
- Kompozit malzeme analizleri
- Akışkan-Yapısal etkileşim analizleri
- Eklemeli imalat analizleri
- Rotordinamiği analizleri
- Yük çıkarım analizleri
- **Manevra Analizleri**







Sonlu Elemanlar Yöntemi ve Adımları

- FEA temel olarak karmaşık mühendislik problemlerini basitleştirerek çözmemizi sağlayan, sonlu sayıda elemanlar kullanılarak sonsuz sayıda bilinmeyen içeren bir sistemin davranışı tahmin edilen bir numerik metottur.
- Sonsuz sayıda bilinmeyen içeren bir fiziksel sistem discretization yöntemiyle sonlu elemanlara bölünür.
- Sonlu elemanlara bağlı denklemlerle kurulan matematik model çözülerek tasarımın belirli koşullara nasıl tepki vereceği saptanır.

Pre-Processing

Geometri sadeleştirme

Malzeme tanımlama

Mesh (1D,2D,3D)

Yükleme ve sınır koşulları

Analysis

Analiz türüne karar verme

Çözüm adımlarına karar verme

Çözüm seçeneklerine karar verme

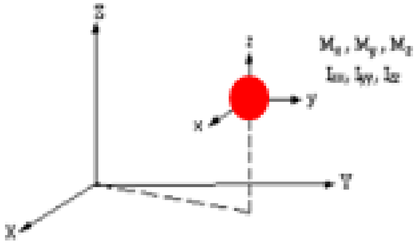
Post-Processing

Sonuçların elde edilmesi ve model gözden geçirme

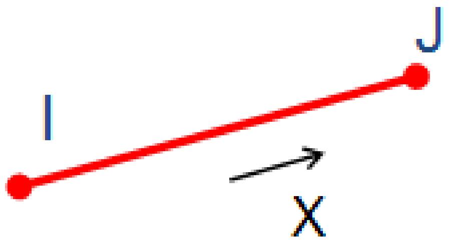
- Görseller
- Grafikler
- Kuvvet, deformasyon, stress, sıcaklık vb.

Sonlu Elemanlar Yöntemi

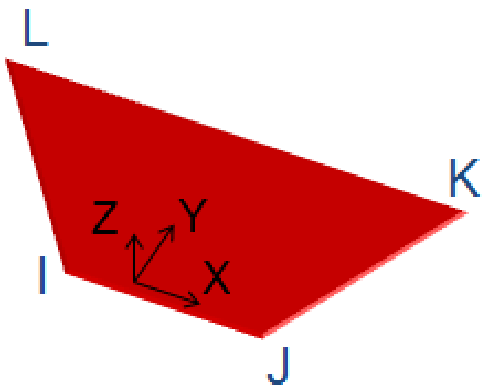
- Eleman tiplerine örnekler:
  - MASS eleman: Noktasal olan kütle elemanlarıdır.
  - LINK eleman: 2 düğüm noktasını birbirine bağlayan çizgi elemanıdır.
  - SHELL eleman: Üçgen veya dörtgen şekle sahip bir alan elemandır.
  - SOLID eleman: Tetrahedral veya brick şekle sahip bir hacim elemanıdır.



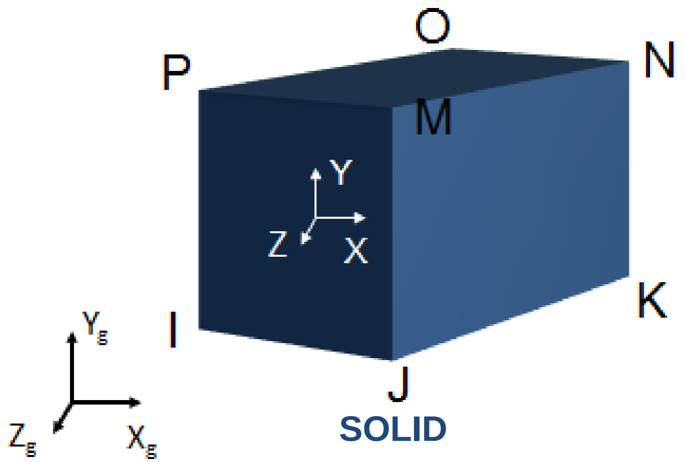
MASS



LINK



SHELL



SOLID

Art Yakıcı Üzerine Gelen Temel Yapısal Yükler

- Liner = Buckling (Delta P), Creep, Thermal Stress, Aero-acoustic vibrations, modal dikkat!
- Flame holder, spray bar = Aero loads, thrust, creep, LCF, HCF, modal dikkat!
- Casing = Manevra, thrust, DeltaP, modal dikkat!

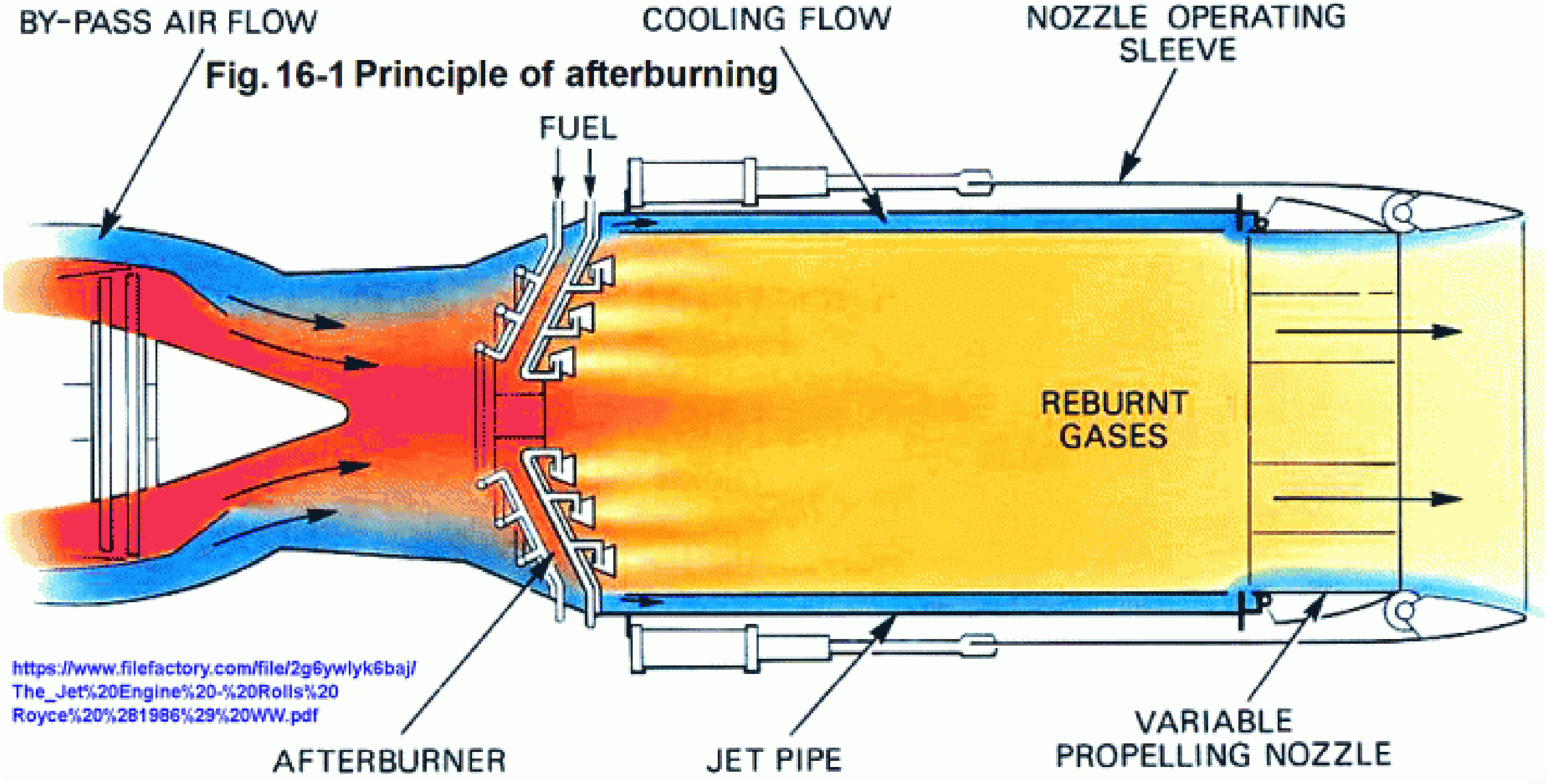
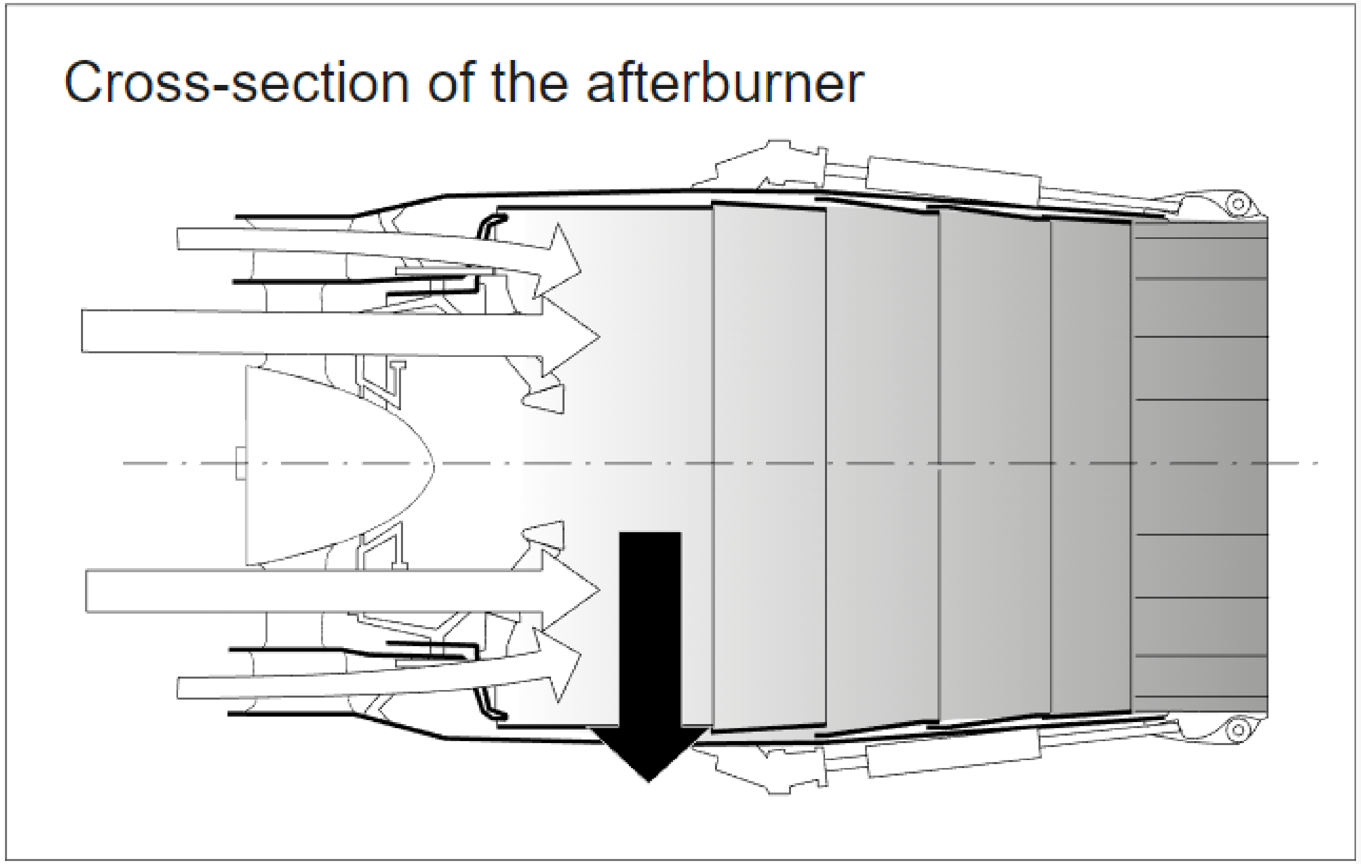


Fig. 16-1 Principle of afterburning

https://www.filefactory.com/file/2g6ywlyk6baj/The_Jet%20Engine%20-%20Rolls%20Royce%20%281986%29%20WW.pdf

Çalışma koşulları içerisinde modal çakışmalar yaşanmamasına dikkat!

Art Yakıcı Üzerine Gelen Temel Yapısal Yükler

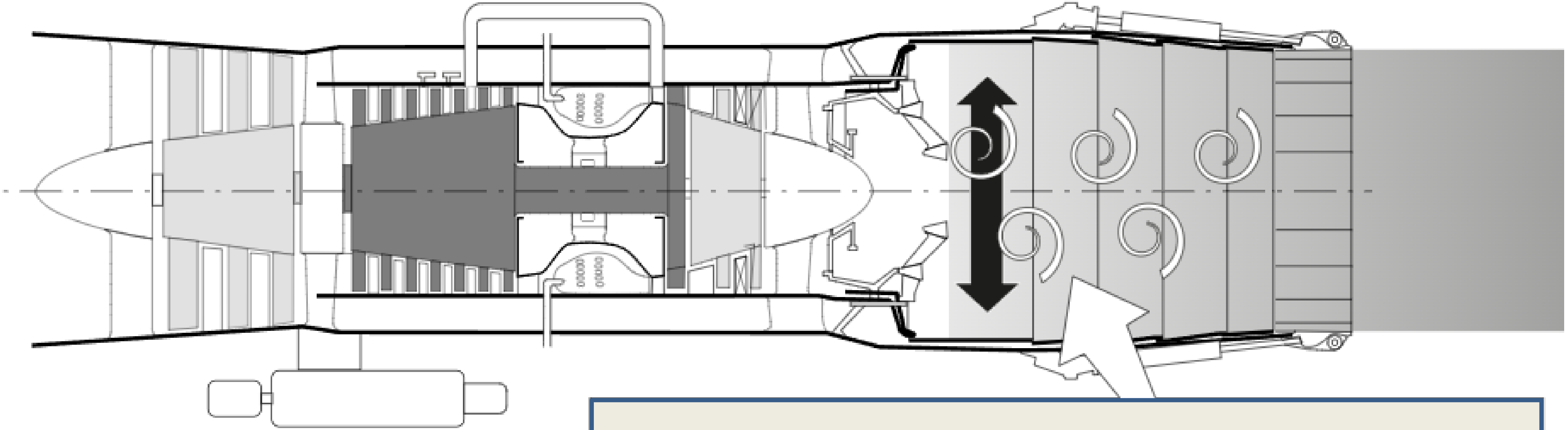


Manevra koşullarında oluşabilecek yüklere dikkat!

Art Yakıcı iç-dış basınç farklarına dikkat!

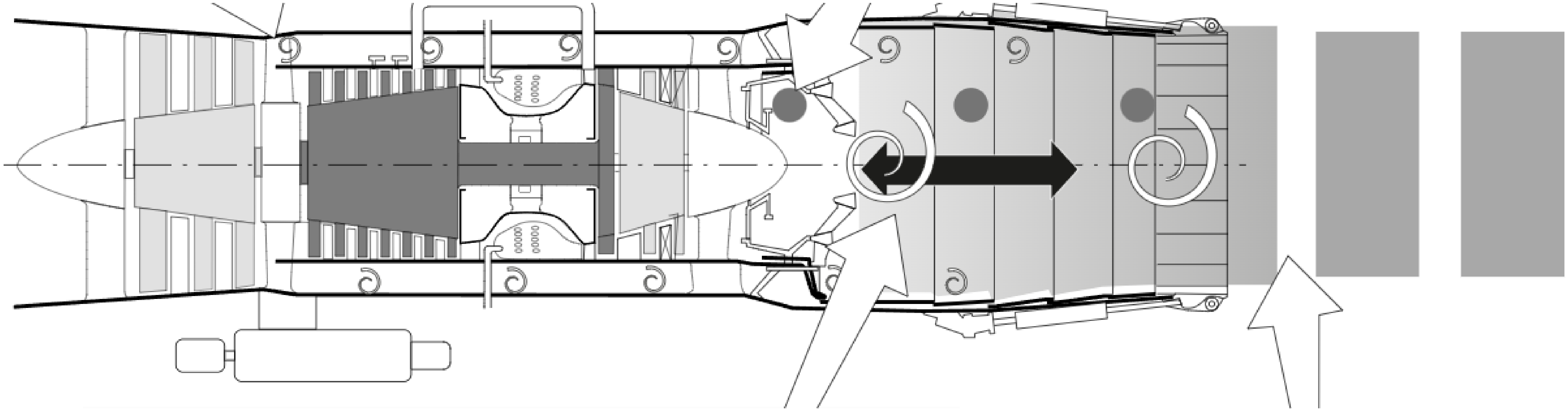
Sıcaklık değişimlerine dikkat!

Art Yakıcı Üzerine Gelen Temel Yapısal Yükler



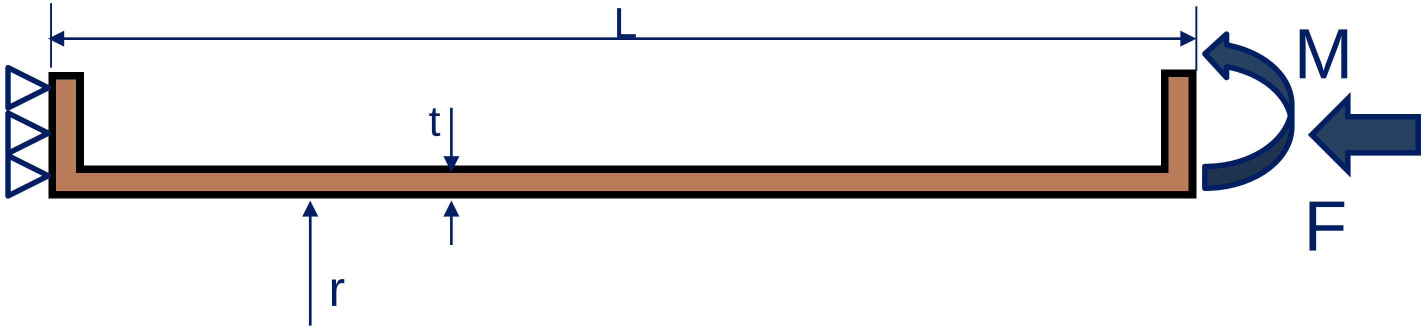
Periyodik aero-acoustic titreşimlere dikkat!

Art Yakıcı Üzerine Gelen Temel Yapısal Yükler



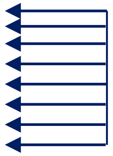
Core engine ve egzoz çıkışı periyodik itki dalgalanmalarına dikkat!

Mukavemet Hesapları ve Analizleri

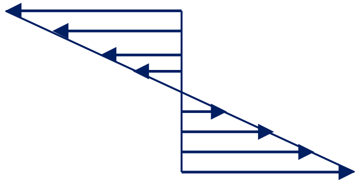


r = 218 mm
t = 2 mm
L = 164 mm
E = 92,000 MPa @ 415°C
M = 4.6 x 10^9 Nmm
F = 82,000 N

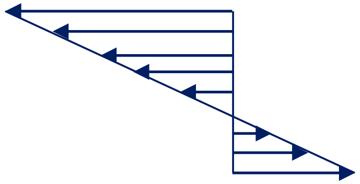
$$\sigma_a = \frac{F}{A} = \frac{82{,}000}{\pi\frac{(440^2-436^2)}{4}} = 29.8\ MPa$$



$$\sigma_b = \frac{M_b * t}{I} = \frac{4.6*10^9*2}{\pi\frac{(440^4-436^4)}{64}} = 140\ MPa$$



$$\sigma_{c,max} = \sigma_b + \sigma_a = 140 + 29.8 = 169.8\ MPa$$



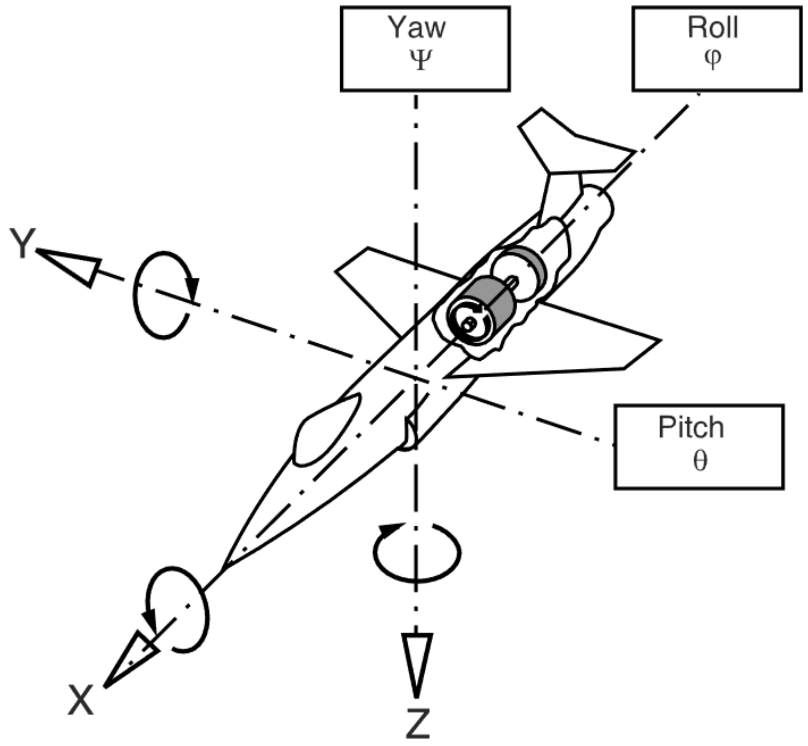
$$\sigma_{T,max} = \sigma_b - \sigma_a = 140 - 29.8 = 110.2\ MPa$$

Manevra Hesapları ve Analizleri

Limit	**X = +/- 5.0 g**	**Y = +/- 5.0 g**	**Z = +/- 5.0 g**
Ultimate	X = +/- 7.5 g	Y = +/- 7.5 g	Z = +/- 7.5 g

- Yukarıda belirtilen manevra koşullarında tasarımlarda kalıcı deformasyon oluşmamalı ve ilgili parçalar fonksiyonlarına sorunsuz devam edebilmelidir!

Flight maneuver axes



Yorulma Hesapları ve Analizleri

Düşük Çevrim Yorulma (LCF):

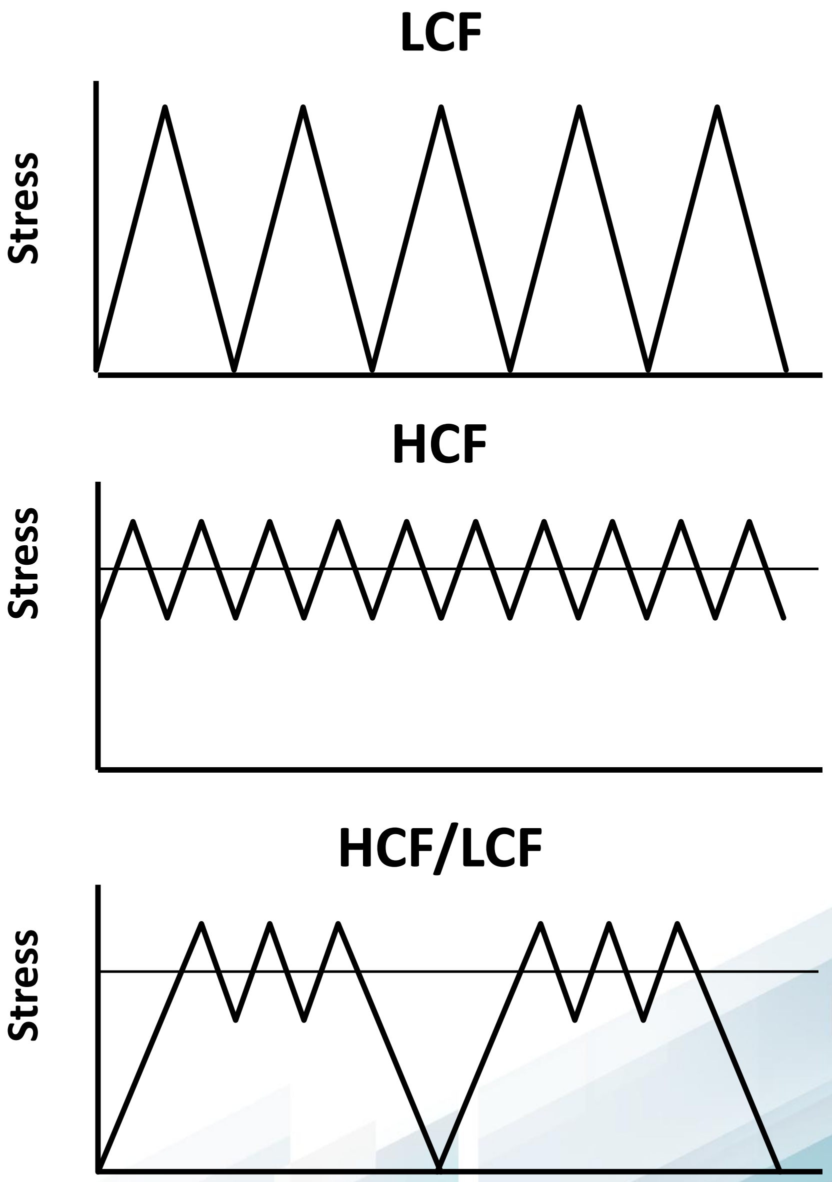
- Hasar tipik olarak 100.000 döngüden az gerçekleşir
- Normalde genel motor çevrimi ile ilişkilendirilen, motor uçuş çevrimi başına 1-2 çevrim
- Gerilme aralıkları tipik olarak akma gerilimi aralığında veya daha fazla

Yüksek Çevrim Yorulma (HCF)

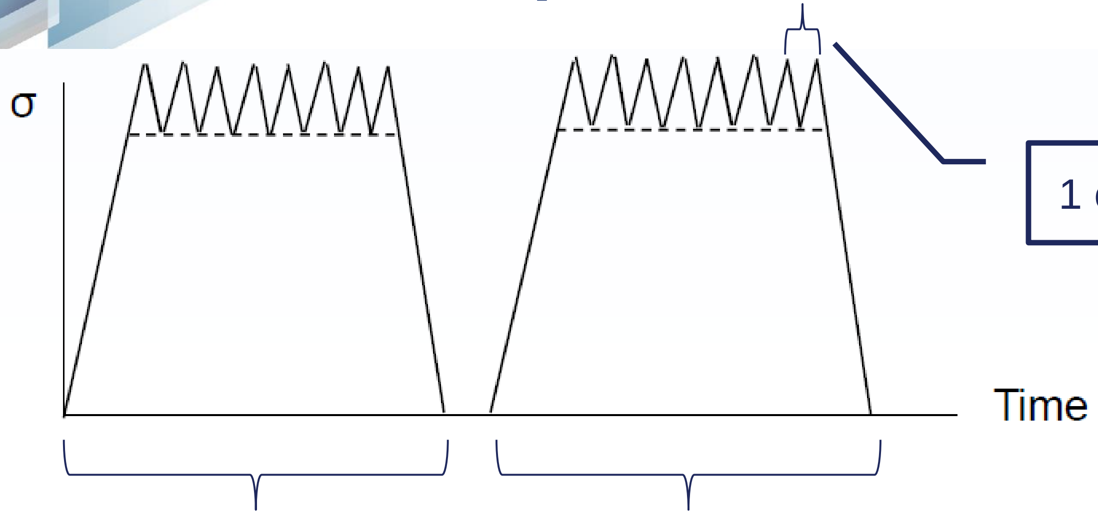
- Hasar tipik olarak 100.000 döngüden fazla çevrimde gerçekleşir.
- Normalde titreşimli gerilme sorunuyla ilişkilendirilir
- Gerilme aralığı genellikle akma geriliminin oldukça altındadır ve genellikle yüksek bir ortalama gerilme ile ilişkilendirilir

LCF/HCF Etkileşimi

- Maks. LCF gerilmesi sırasında üst üste binen titreşim gerilmesi



Yorulma Hesapları ve Analizleri

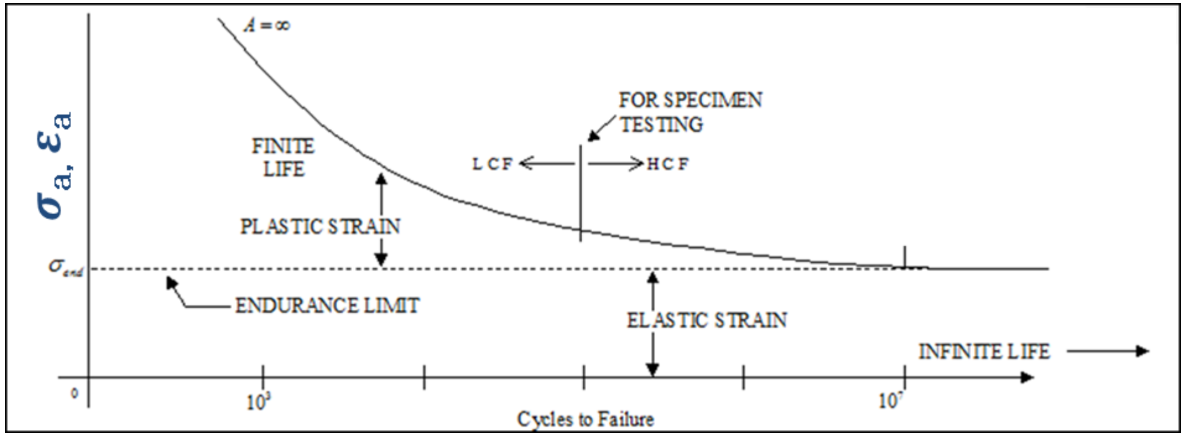


1 cycle HCF ➔ Titreşim

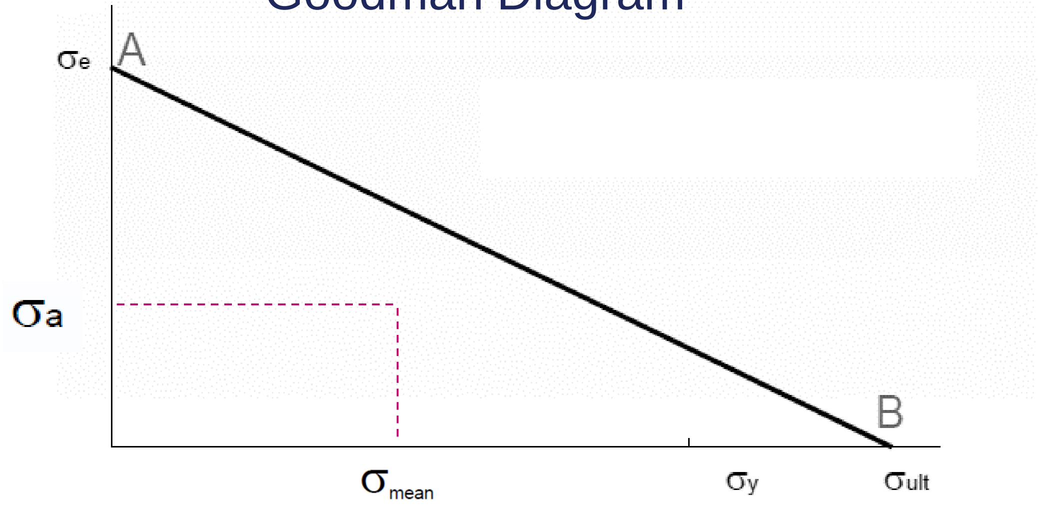
1 cycle LCF ➔ Art yakıcı açılış - kapanış

Dikkat!

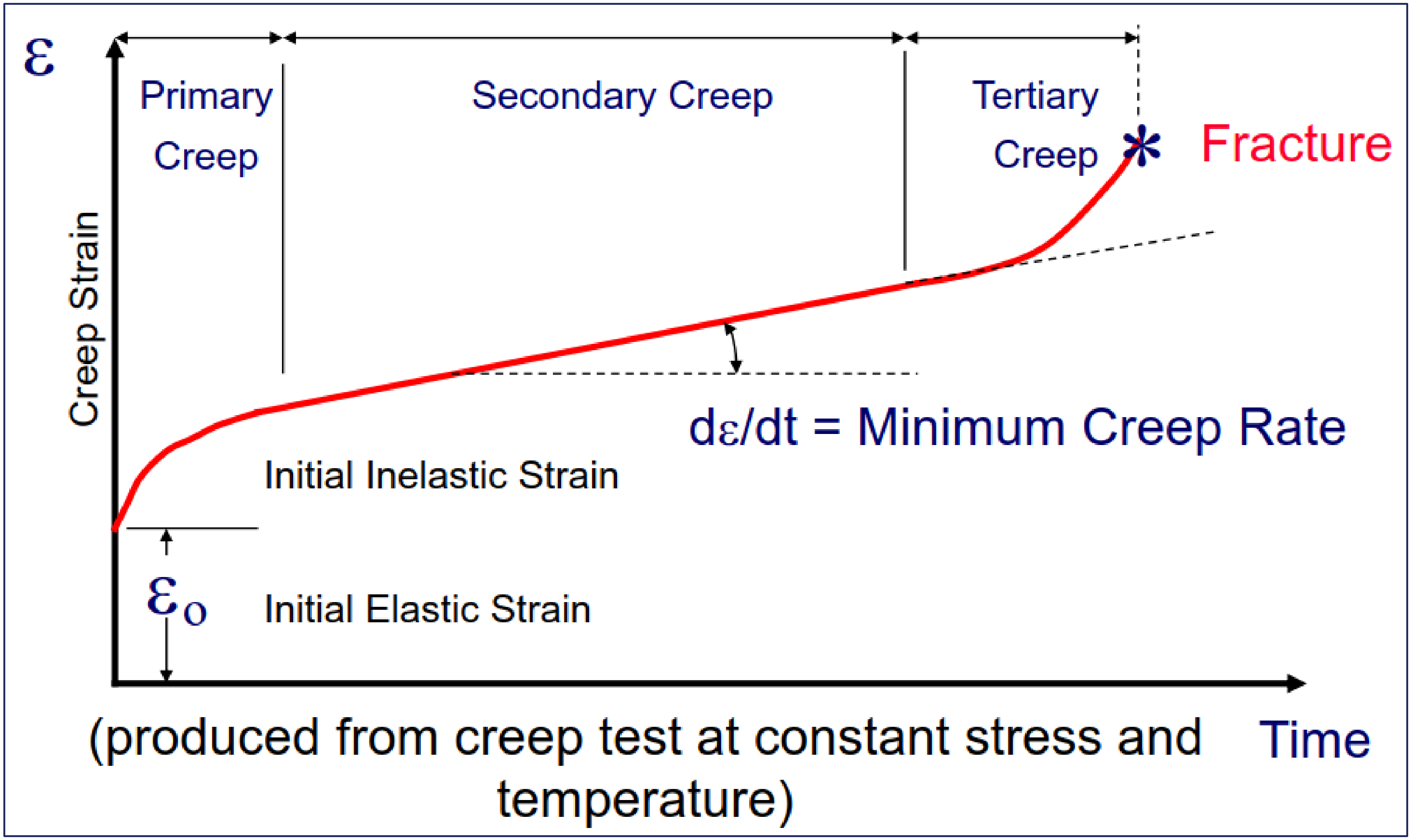
- Uygulanan gerilme/gerinim
- Yük tekrar sayısı
- Malzeme özellikleri
- Sıcaklık



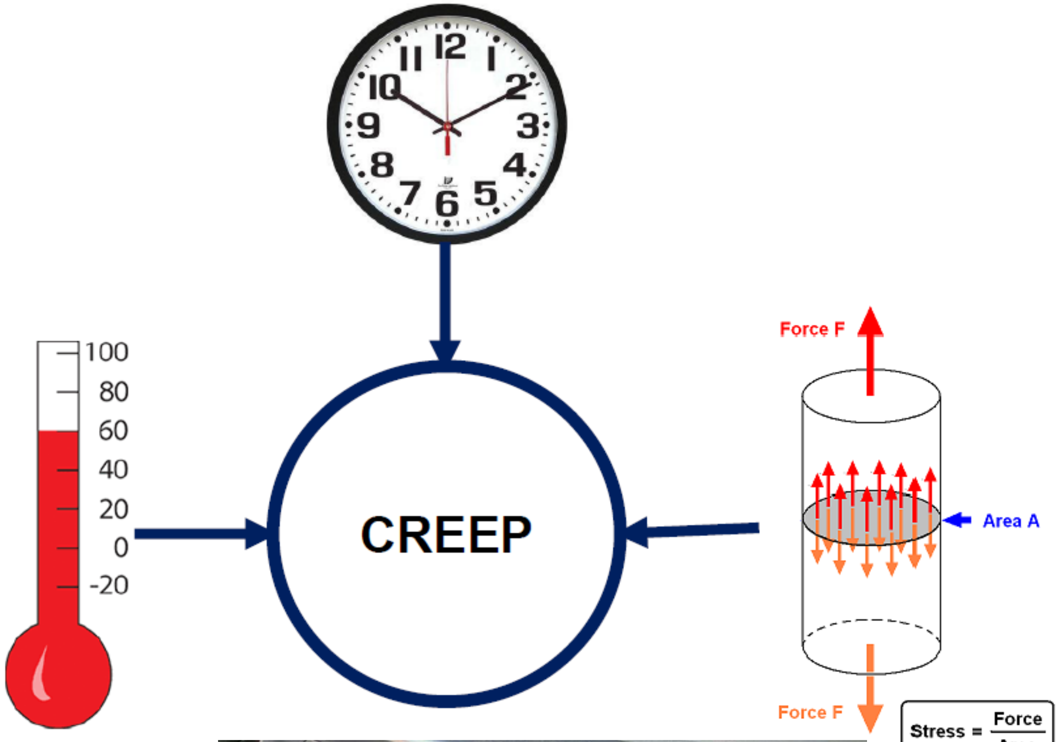
Goodman Diagram



Sürünme (Creep) Hesapları ve Analizleri



(produced from creep test at constant stress and temperature)

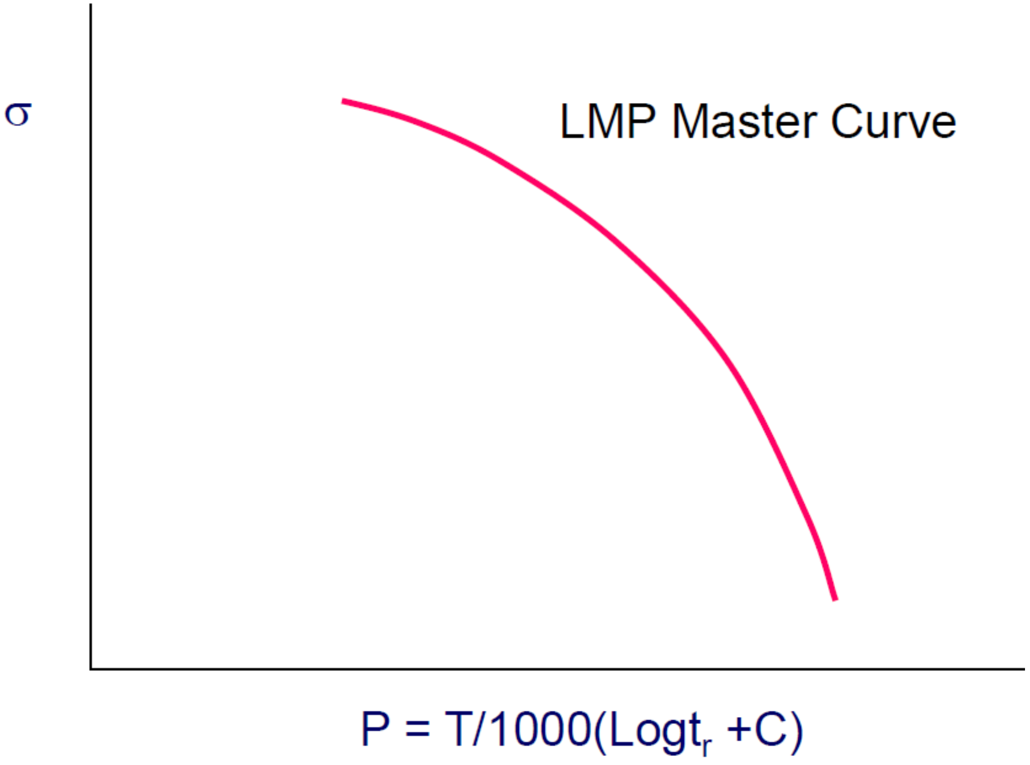


Sürünme (creep) sonrası LPT bladeleri

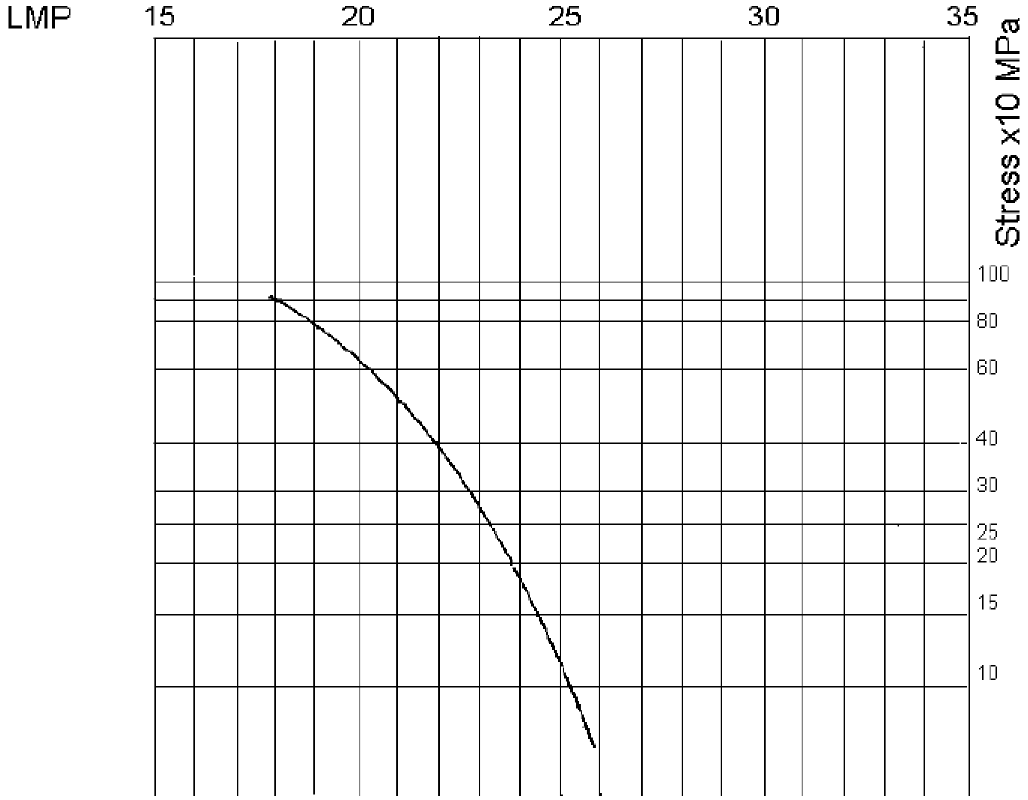
Sürünme (Creep) Hesapları ve Analizleri

Larson Miller Parameter

$$P = T/1000(20 + \log t_r)$$



Larson-Miller Parameter for Nimonic 80A

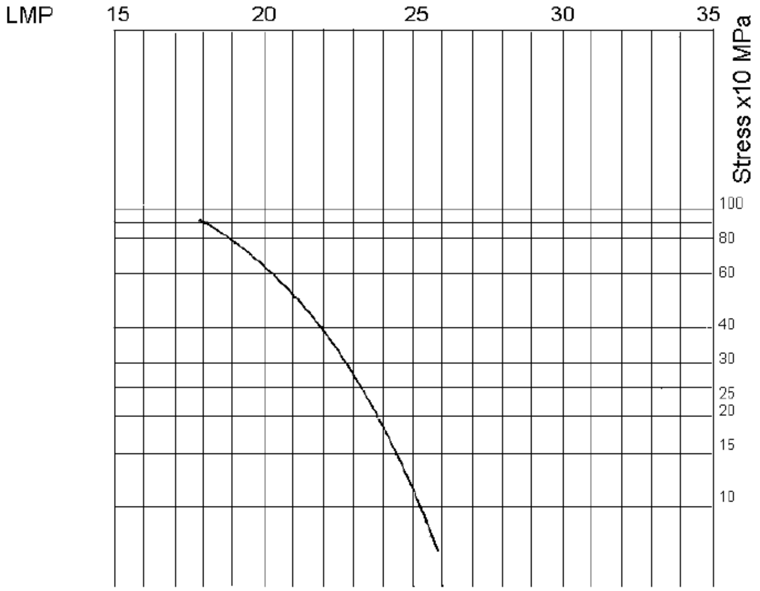


Sürünme (Creep) Hesapları ve Analizleri

Örnek bir uçuş zarfı:

	Time (min)
Take-off	1.5
Climb	15.0
Cruise	103.0
Low Ratings	30.0
Reverse Thrust	0.5
TOTAL	150.0

Larson-Miller Parameter for Nimonic 80A

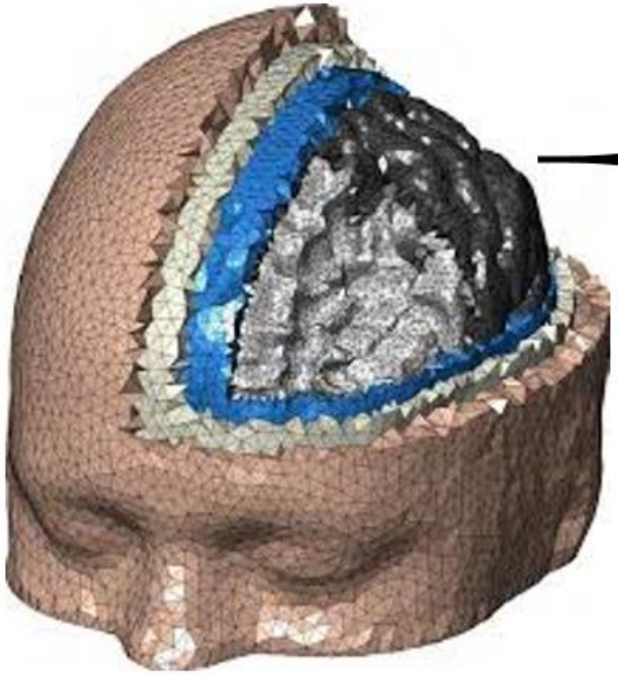


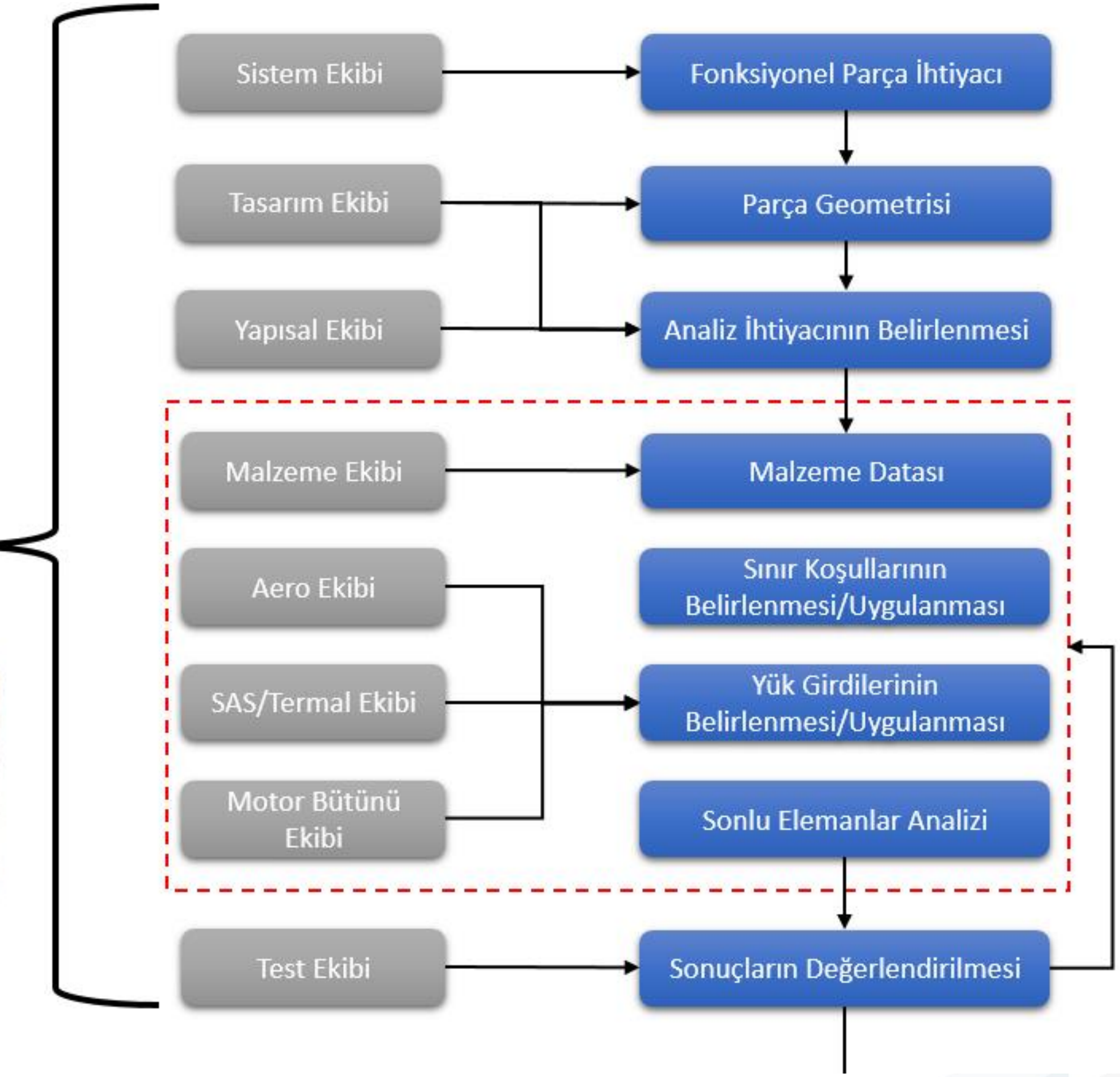
	T°K	Stress (MPa)	P	t_f (hours)
Take-off	1000	300	22.8	631
Climb	1100	200	23.9	53.4
Cruise	950	150	24.5	615848
Low Ratings	925	100	25.3	224569800
Reverse Thrust	1000	300	22.8	631

Operation	t/t_f
Take-off	0.00004
Climb	0.0047
Cruise	0.0000028
Low Ratings	$2.22\text{x}10^{-9}$
Reverse Thrust	0.0000132
Total creep life consumed	= 0.0048

$$\sum \frac{t}{t_f}$$

Analiz Süreci Akış Şeması





Sistem Ekibi → Fonksiyonel Parça İhtiyacı

Tasarım Ekibi → Parça Geometrisi

Yapısal Ekibi → Analiz İhtiyacının Belirlenmesi

Malzeme Ekibi → Malzeme Datası

Aero Ekibi

SAS/Termal Ekibi

Motor Bütünü Ekibi

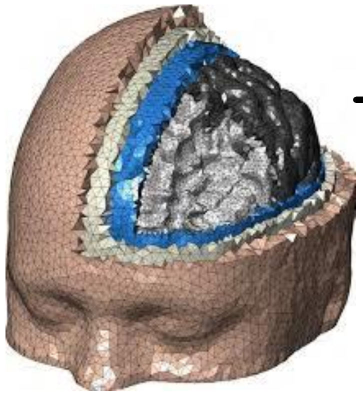
Sınır Koşullarının Belirlenmesi/Uygulanması

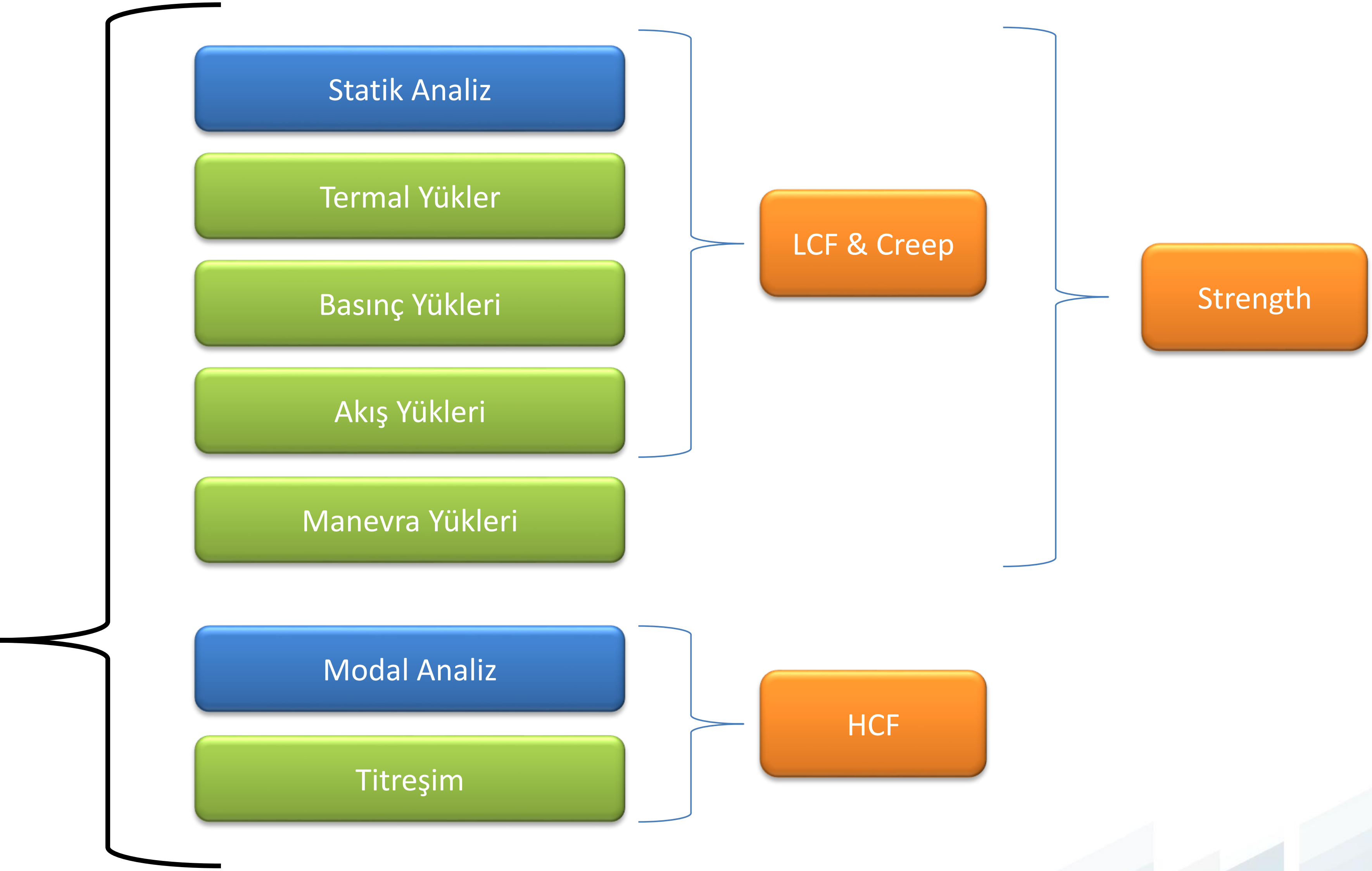
Yük Girdilerinin Belirlenmesi/Uygulanması

Sonlu Elemanlar Analizi

Test Ekibi → Sonuçların Değerlendirilmesi

Modal, Dinamik Hesaplar ve Analizleri





Statik Analiz

Termal Yükler

Basınç Yükleri

Akış Yükleri

Manevra Yükleri

Modal Analiz

Titreşim

LCF & Creep

Strength

HCF

Geometrik Model Oluşturma

- Analizi gerçekleştirilecek parçalara ait CAD modeller ‘parça resmi (drawing)’ ne göre mekanik tasarım ekibi tarafından hazırlanır.
- Mevcut olan modellerdeki bazı basitleştirmeler, değişiklikler yapısal analiz mühendisleri tarafından da parça resmine bağlı kalınacak şekilde gerçekleştirilir.
- 3D modelleme yapılmayacak olan parçalar için gerekli operasyonlar gerçekleştirilir.

Siemens PLM Software
NX

Version 12.0
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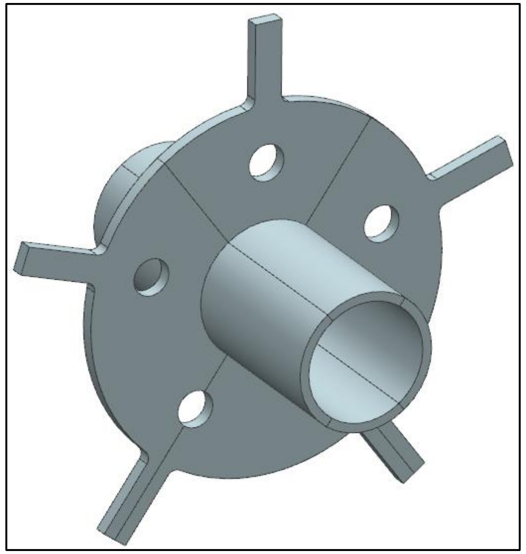
Design Modeler

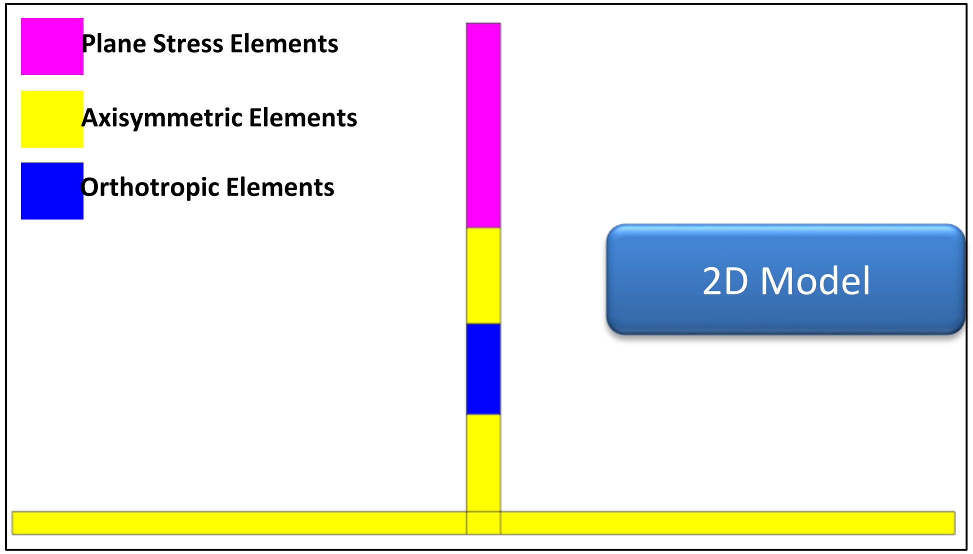
SPACECLAIM
CORPORATION

Yapılan geometrik basitleştirmeler raporda açıklanmalıdır.

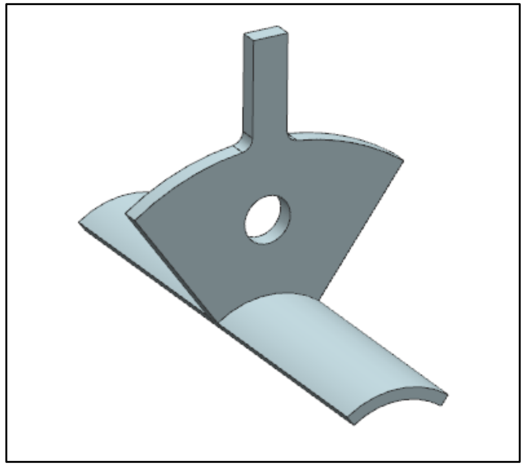
Geometrik Model Oluşturma



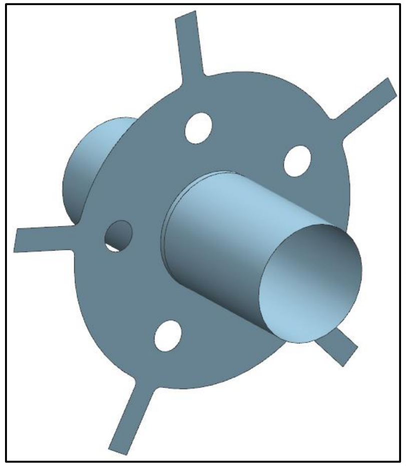
3D Model



2D Model



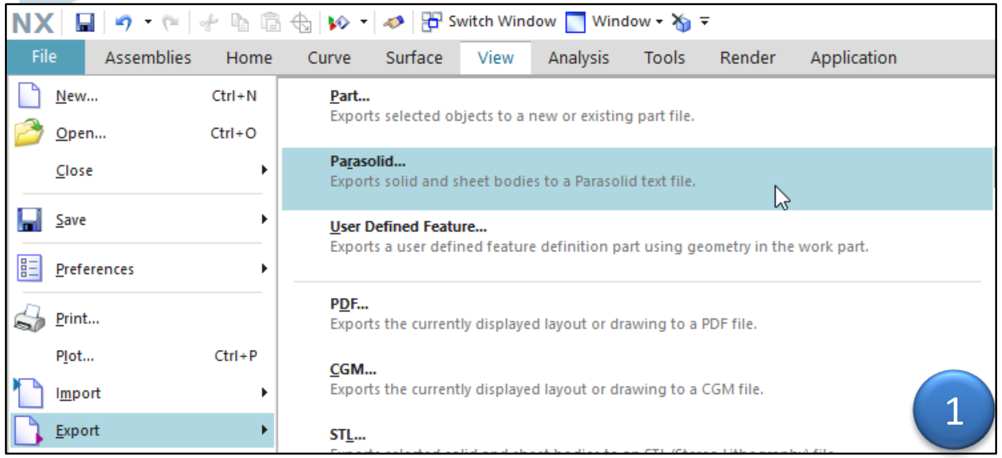
Cyclic Simetrik Model



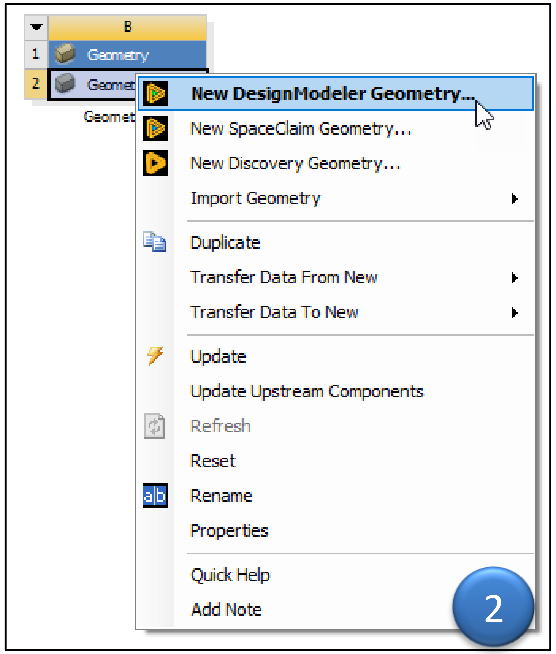
Shell-Beam Model

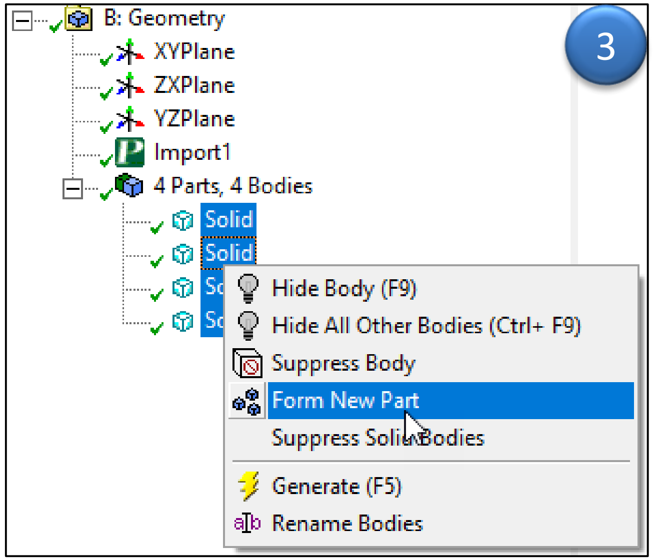
Seçilen modelleme metodu ve sebebi raporda açıklanmalıdır.

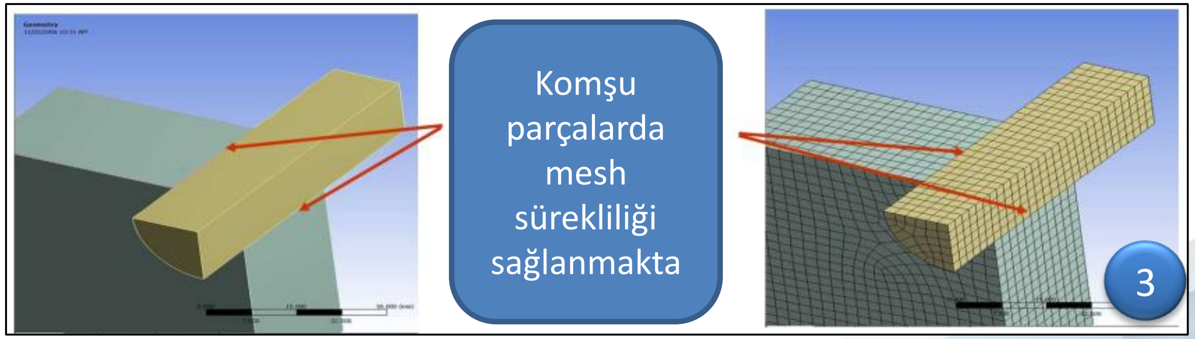
Geometrik Model Oluşturma



1. Geometri dışarıda hazırlandıysa parasolid,iges vb. bir formata dönüştürülür.
2. İlgili analiz programının geometri tool'una import edilir.
3. Eğer parça mesh atma kolaylığı için birden çok parçaya bölündüyse ilgili body'ler mesh sürekliliğini korumak amacıyla birleştirilir. Aksi takdirde farklı parçalar olarak algılanacaktır, kontak tanımlaması yapmak gerekecektir.



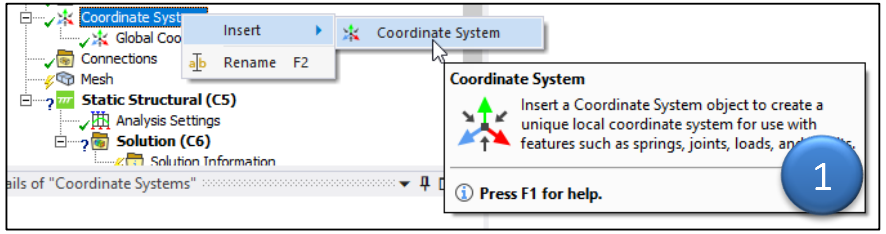



Komşu parçalarda mesh sürekliliği sağlanmakta

Mesh kolaylığı için yapılan geometrik operasyonlar açıklanmalıdır.

Koordinat Sistemi Oluşturma

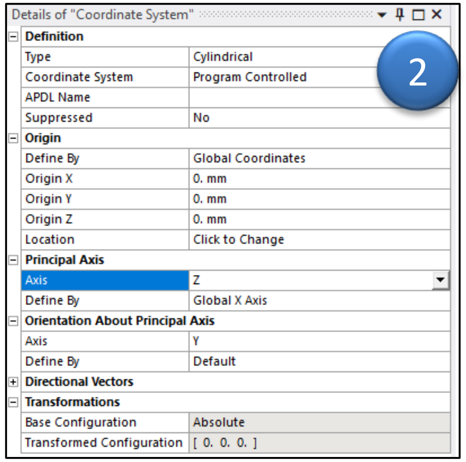
1. Global koordinat dışında referans koordinat eklenir.
2. Radial veya tangential sınır koşulu verilecek veya sonuç okunacak ise silindirik koordinat sistemi tanımlanır
3. Silindirik koordinat sisteminde X radyal yönde, Y tangential yönde ve Z eksenel yönde olmalıdır.
4. Koordinat sistemi ihtiyaç halinde ötelenebilir, döndürebilir veya ters yöne çevrilebilir.
5. Cyclic simetri model kullanılacak ise silindirik koordinat sistemi kullanılması şarttır.



Coordinate System

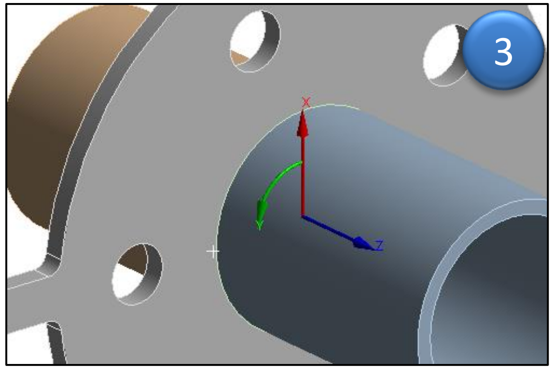
Insert a Coordinate System object to create a unique local coordinate system for use with features such as springs, joints, loads, an

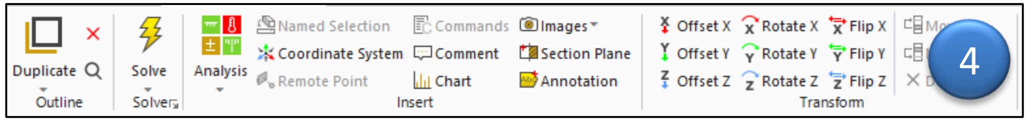
Press F1 for help.



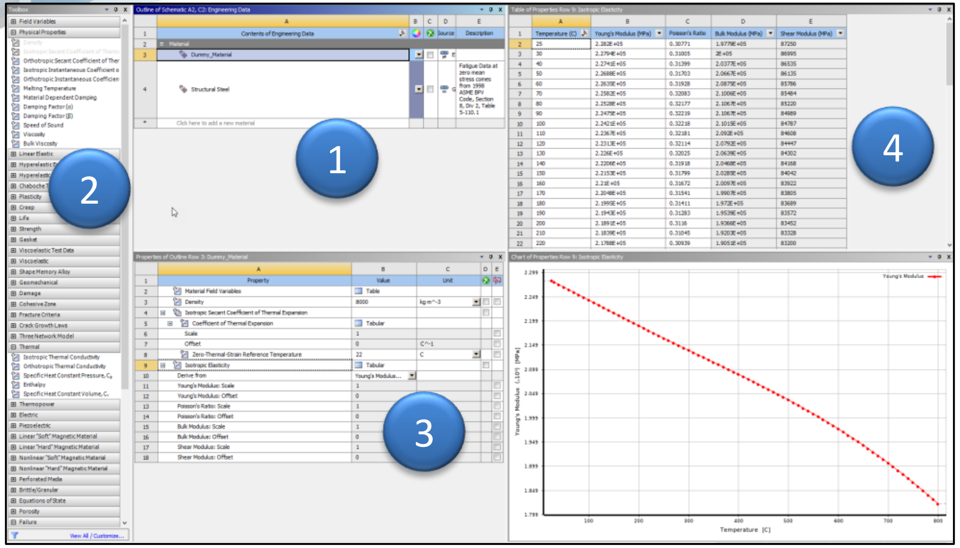
Details of "Coordinate System"

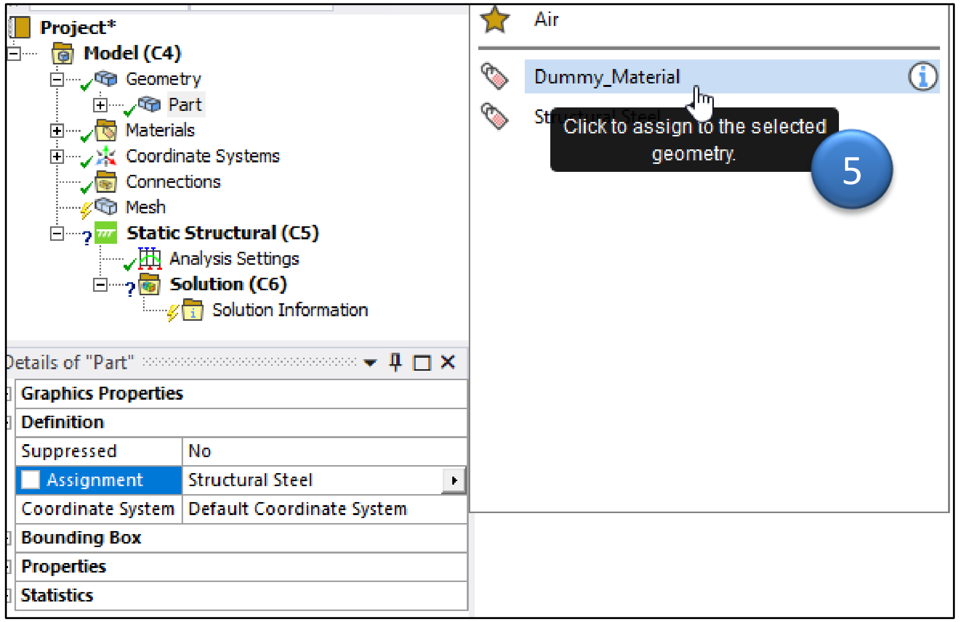
Definition	
Type	Cylindrical
Coordinate System	Program Controlled
APDL Name	
Suppressed	No
Origin	
Define By	Global Coordinates
Origin X	0. mm
Origin Y	0. mm
Origin Z	0. mm
Location	Click to Change
Principal Axis	
Axis	Z
Define By	Global X Axis
Orientation About Principal Axis	
Axis	Y
Define By	Default
Directional Vectors	
Transformations	
Base Configuration	Absolute
Transformed Configuration	[0. 0. 0.]





Malzeme Tanımlama





Click to assign to the selected geometry.

Details of "Part"

Graphics Properties	
Definition	
Suppressed	No
Assignment	Structural Steel
Coordinate System	Default Coordinate System
Bounding Box	
Properties	
Statistics	

1. Malzeme kartı oluşturulur.
2. Malzeme kartına ilgili malzeme özellikleri eklenir.
3. Malzeme özelliklerinin birimi ayarlanır ve uygun değerler girilir.
4. Sıcaklığa bağlı değerler tabular data olarak girilir.
5. Modelde her parça için ilgili malzeme datası seçilir.

Statik Analiz

- Density
- Elastic Modulus (T)
- Poisson’s Ratio (T)
- Thermal Expansion Coefficient (T)

$$[K]\{u\}=[F]$$

Modal Analiz

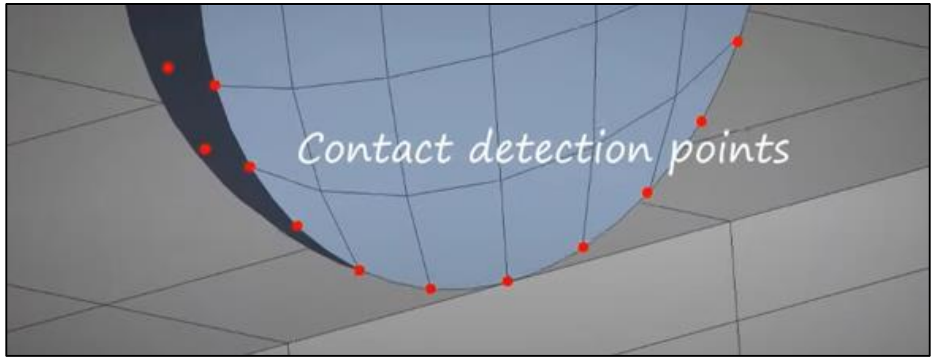
- Density
- Elastic Modulus (T)
- Poisson’s Ratio (T)

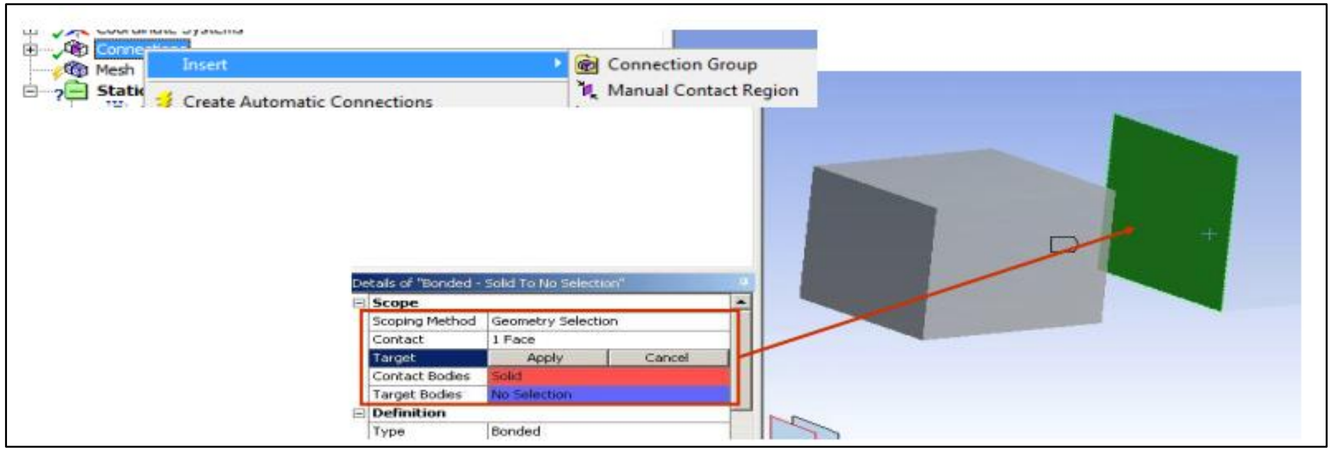
$$([K]-\omega^2[M])\{\psi_i\}=\{0\}$$

Kullanılan malzeme datası ve referans raporda paylaşılmalıdır.

Kontak Oluşturma

- Eğer modelde birden fazla parça etkileşim içerisindeyse kontak elemanları tanımlanmalıdır.
- Contact/Target seçimi yapılırken aşağıdaki özelliklere sahip yüzey kontak olarak belirlenir.
  - Daha sık mesh atılan yüzey
  - Düz ya da konkav’a karşılık konvex yüzey
  - Yumuşak malzemeye sahip yüzey

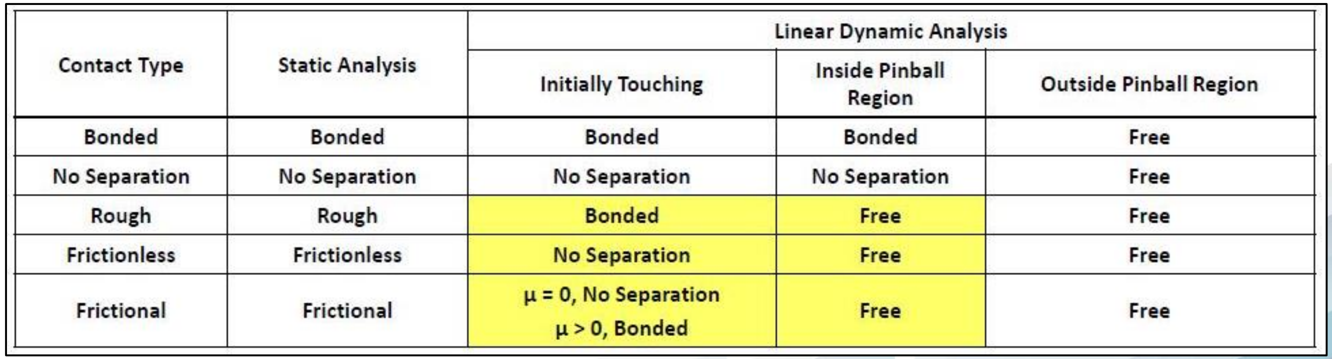




Details of "Bonded - Solid To No Selection"

Scope	
Scoping Method	Geometry Selection
Contact	1 Face
Target	
Contact Bodies	Solid
Target Bodies	No Selection
Definition	
Type	Bonded

Kontak kullanılırsa kontak özellikleri raporda açıklanmalıdır.

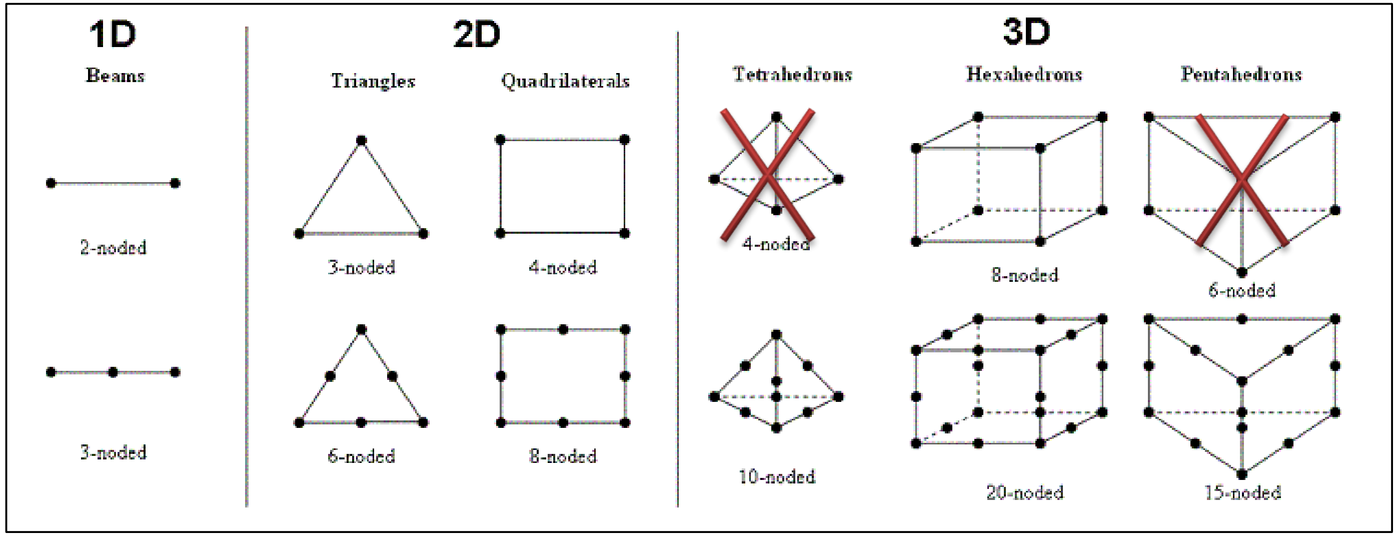


Contact Type	Static Analysis	Linear Dynamic Analysis		
		Initially Touching	Inside Pinball Region	Outside Pinball Region
Bonded	Bonded	Bonded	Bonded	Free
No Separation	No Separation	No Separation	No Separation	Free
Rough	Rough	Bonded	Free	Free
Frictionless	Frictionless	No Separation	Free	Free
Frictional	Frictional	$\mu = 0$, No Separation $\mu > 0$, Bonded	Free	Free

Mesh

- Quadratic elemanlar lineer elemanlara göre daha iyi sonuç verse de zaman anlamında maliyetlidir.
- Piramit ve Wedge elemanlar Hourglassing, shear locking, volumetric locking gibi fenomenler nedeniyle yanlış sonuç verebilir

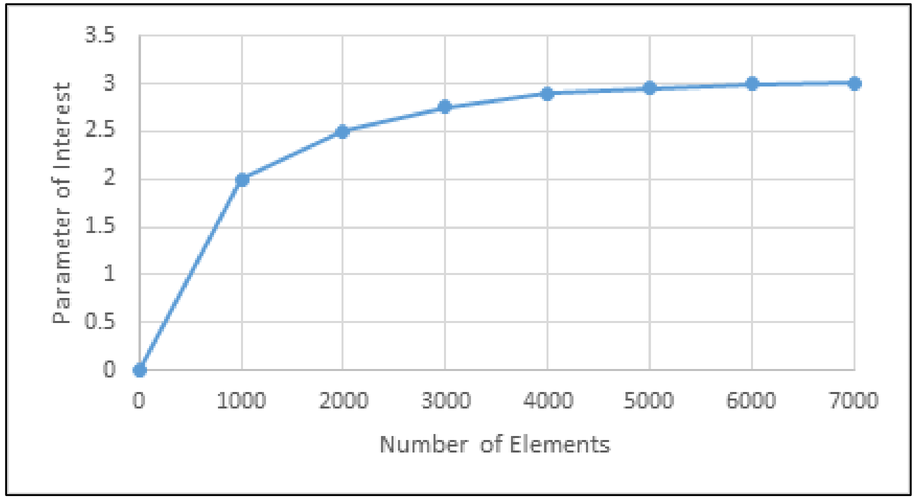
Linear Elements	Quadratic Elements
Linear Shape Function	Quadratic Shape function
Mostly constant state of stress within a single element	Linear variation of stress within a single element
Cannot represent curved edges and surfaces accurately	Can represent curved edges and surfaces accurately
Highly sensitive to element distortion	Relatively less sensitive to element distortion
Generally only acceptable if you are only interested in nominal stress results	Recommended if you are interested in accurate stress distribution
Need to use a large number elements to resolve high stress gradients	Give better results than linear elements, often with fewer elements
Generally, computationally less expensive (simulation runs fast)	Generally, computationally more expensive



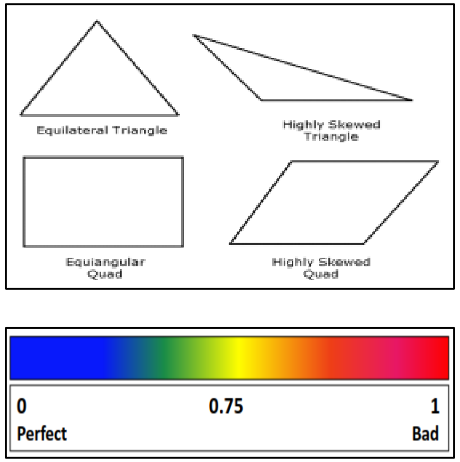
Mesh Kalitesi

- Radyuslar minimum quadratic 3, linear 6 eleman ile meshlenmeli.
- Delik ve radyuslar hexa elemanlar ile modellenmeli.
- Kalınlıkta minimum quadratic 2, linear 4 eleman kullanılmalı.
- Kritik gerilme bölgelerinde mesh kalitesi standartlarıyla uyumlu olunmalı

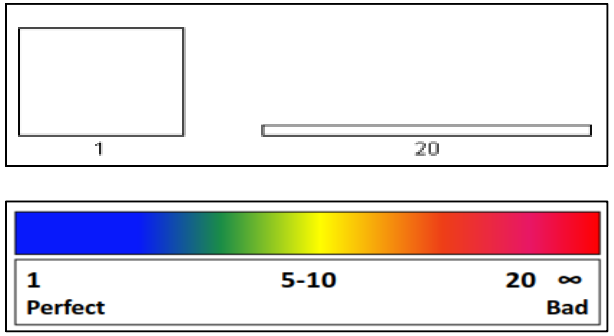
Kritik gerilme bölgelerinin sonuçları verilirken mesh yapısı da gösterilmeli, kriter kontrolü yapılacak bölge için mesh yakınsama çalışması gerçekleştirilmelidir.



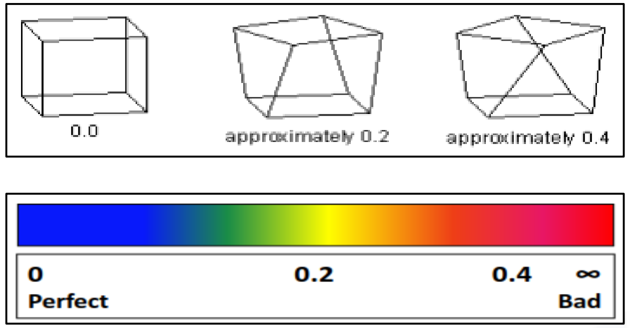
Mesh Yakınsama Çalışması



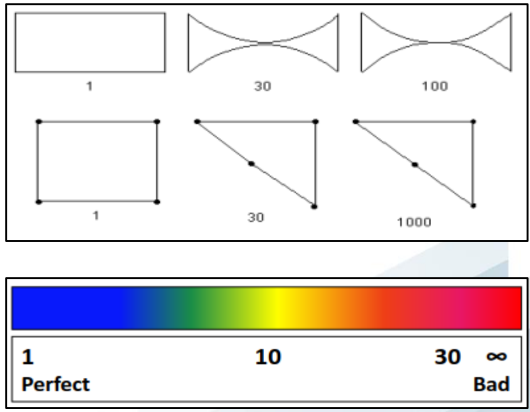
Skewness



Aspect Ratio

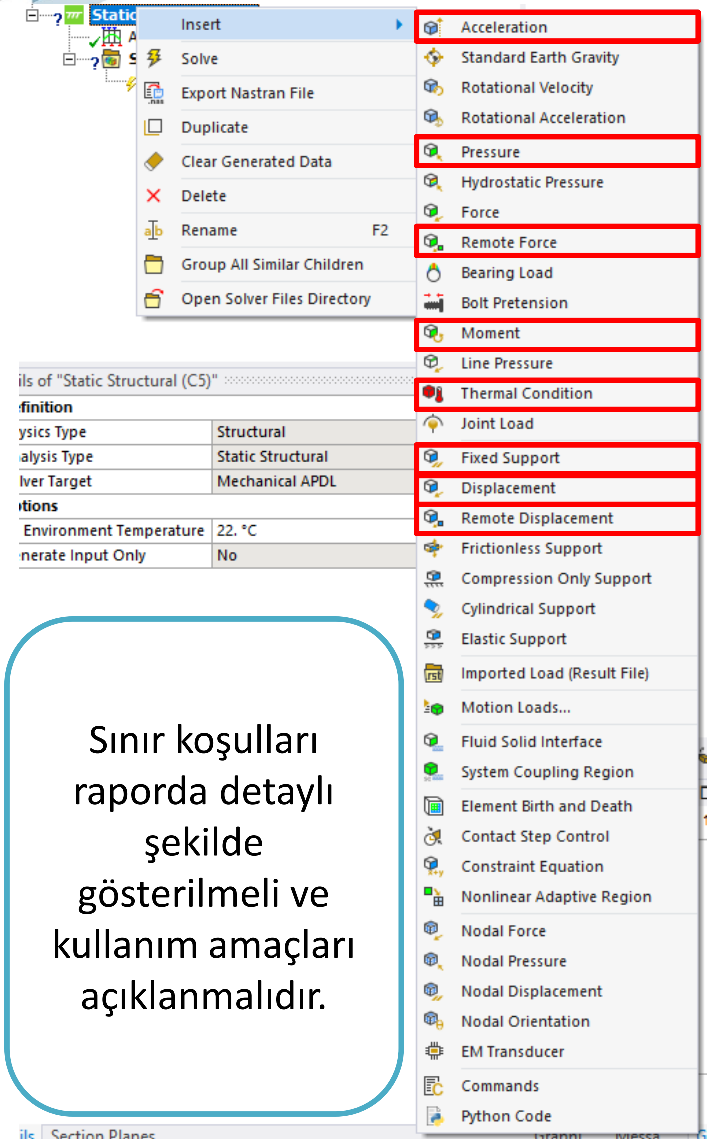


Warping Ratio



Jacobian Ratio

Sınır Koşulları



ils of "Static Structural (C5)"

finition

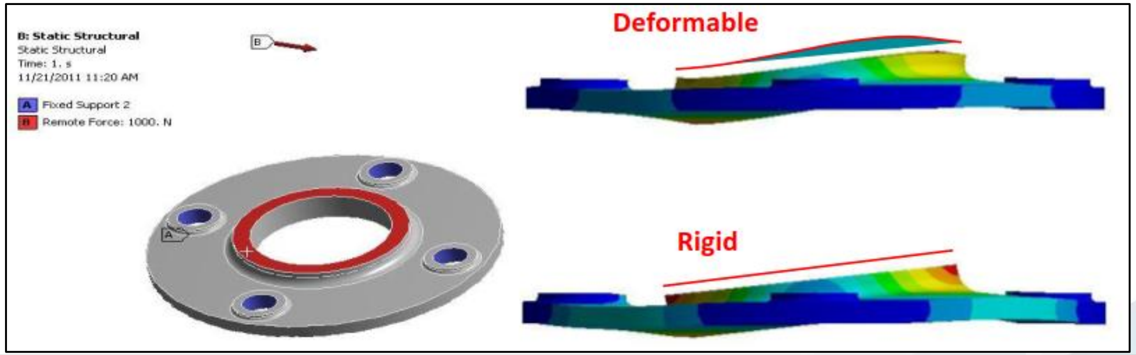
ysics Type	Structural
alysis Type	Static Structural
lver Target	Mechanical APDL

tions

Environment Temperature	22. °C
nerate Input Only	No

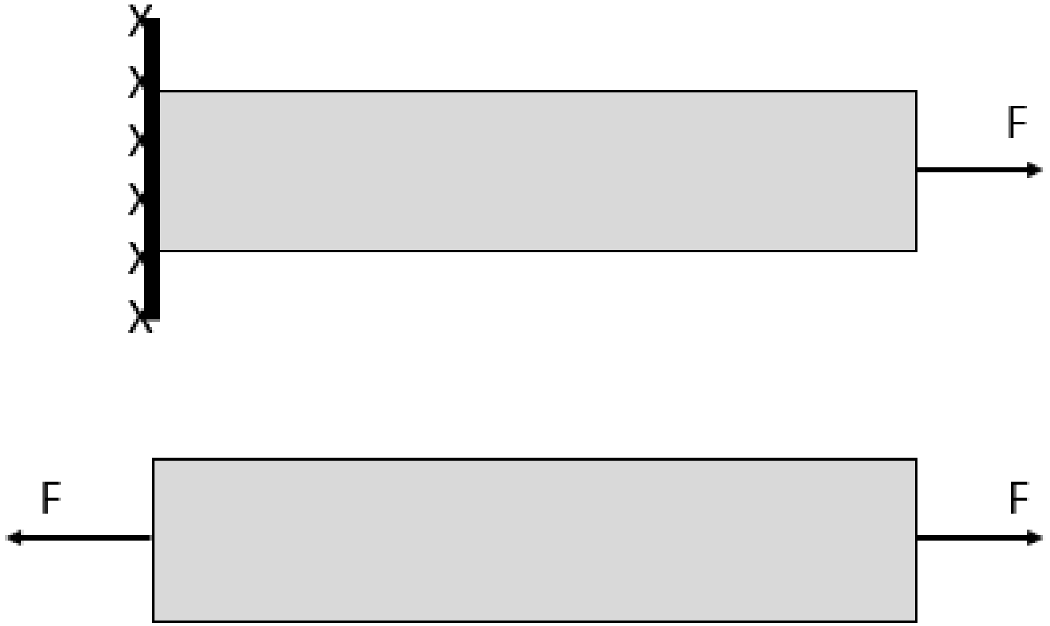
Sınır koşulları raporda detaylı şekilde gösterilmeli ve kullanım amaçları açıklanmalıdır.

- Acceleration - seçeneğiyle çizgisel ivmeler tanımlanabilir. X, Y, Z yönleri ayrı adımlarda tanımlanmalıdır.
- Pressure - seçeneğiyle hem iç ve dış basınçlar hem de akış kaynaklı net yükler ilgili yüzeylere uygulanmalıdır.
- Fixed support - tüm DOF'ları sınırlandırır.
- Displacement – Kartezyen veya Silindirik koordinat sisteminde seçilen DOF'ları sınırlandırır. Örneğin radyal yönde bir sınırlandırma verilecek ise bu seçenek kullanılabilir.
- Remote Force ve Displacement remote point aracılığıyla tanımlanmaktadır. İlgili bölgeyi deformable tanımlama ihtiyacında kullanılır.

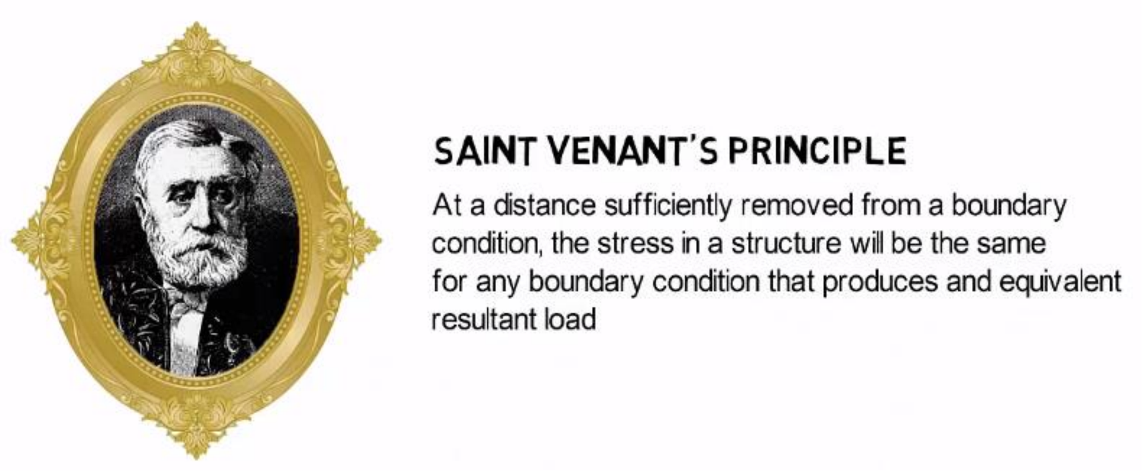


Sınır Koşulları

- Aşağıdaki iki yükleme tipi için aynı stress sonucunu mu bekleriz?



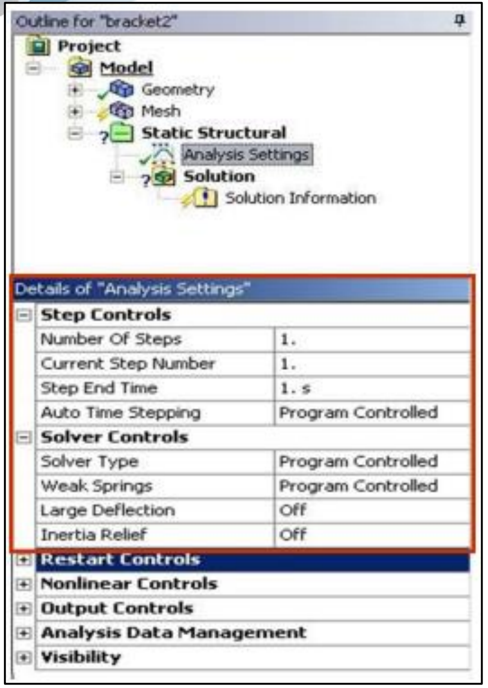
- Lineer Static Analysis Formulation
  - {F}=[K]{x}



SAINT VENANT'S PRINCIPLE

At a distance sufficiently removed from a boundary condition, the stress in a structure will be the same for any boundary condition that produces and equivalent resultant load

Statik Analiz

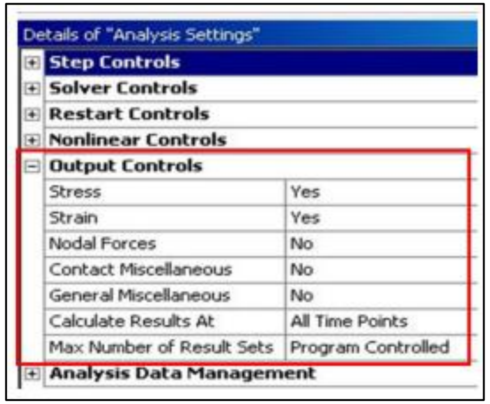


Outline for "bracket2"

- Project
  - Model
    - Geometry
    - Mesh
    - Static Structural
      - Analysis Settings
      - Solution
        - Solution Information

Details of "Analysis Settings"

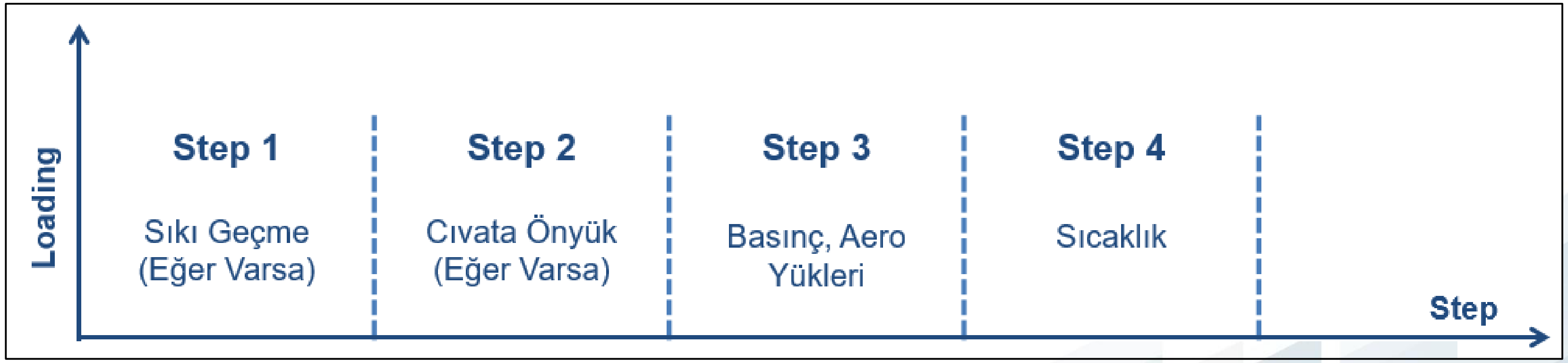
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	Program Controlled
Large Deflection	Off
Inertia Relief	Off
Restart Controls	
Nonlinear Controls	
Output Controls	
Analysis Data Management	
Visibility	



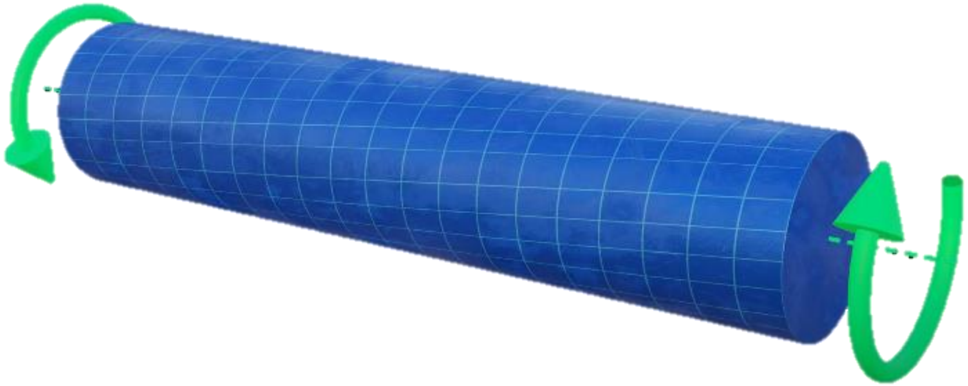
Details of "Analysis Settings"

Step Controls	
Solver Controls	
Restart Controls	
Nonlinear Controls	
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Contact Miscellaneous	No
General Miscellaneous	No
Calculate Results At	All Time Points
Max Number of Result Sets	Program Controlled
Analysis Data Management	

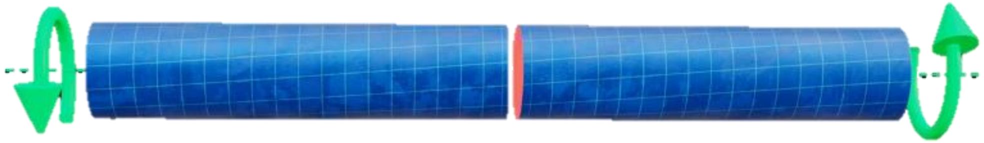
- Number of steps – Analiz birden fazla adıma çıkarılır. Adım-2, Adım-3 ve Adım-4 incelenerek hangi yükün ne kadar etkisi olduğu tespit edilir.
- Solver Control - Direct veya Iterative solver ile çözüm alınabilir.
- Output Controls – Sonuç dosyasına yazdırılacak değerler seçilir.
- Small Deflection Theory
- Lineer Elastik Malzeme özelliği



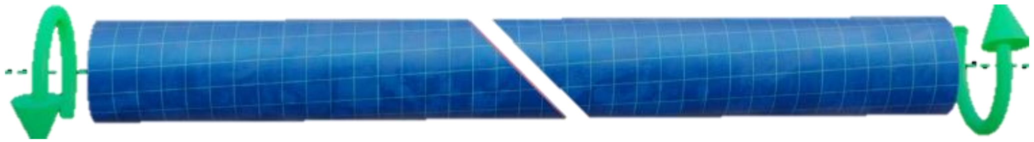
Şaft Failure

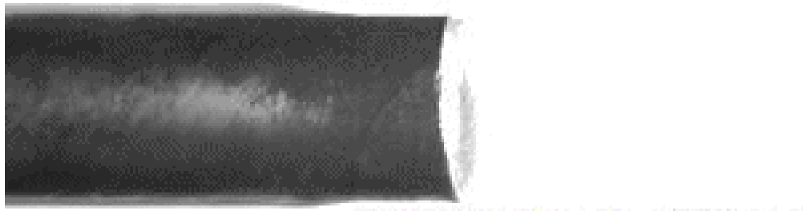


A)



B)



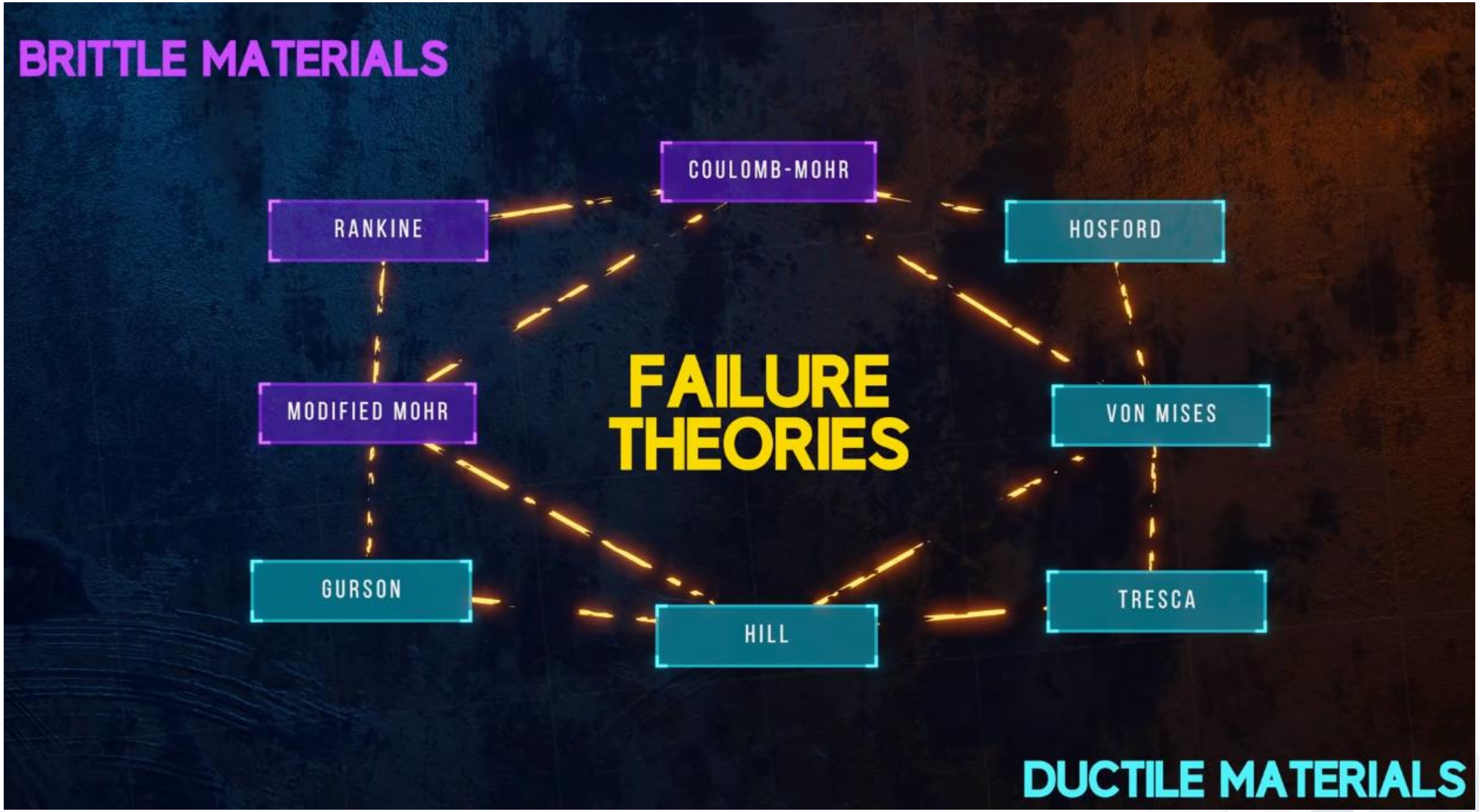


Sünek Malzeme- Statik Yükleme - Torsion Failure

Gevrek Malzeme – Statik Yükleme - Torsion Failure

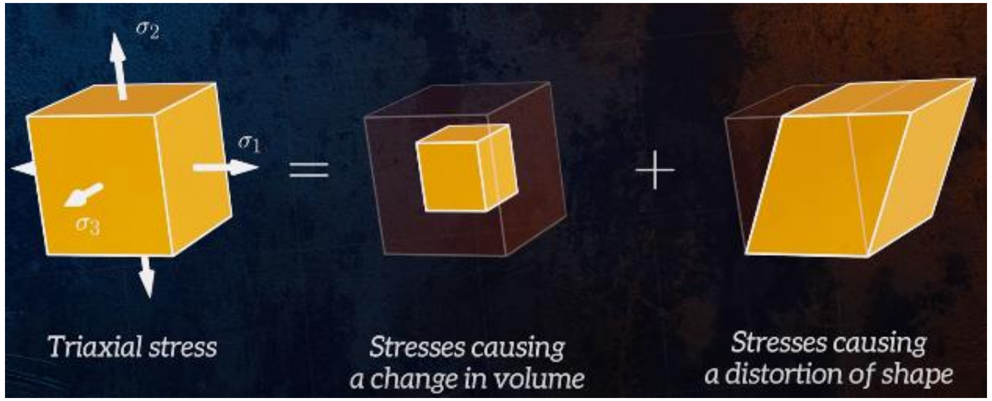
Sünek Malzeme -Dinamik Yükleme - Torsion Failure

Kırılma Teorileri



Max Distortion Energy Theory

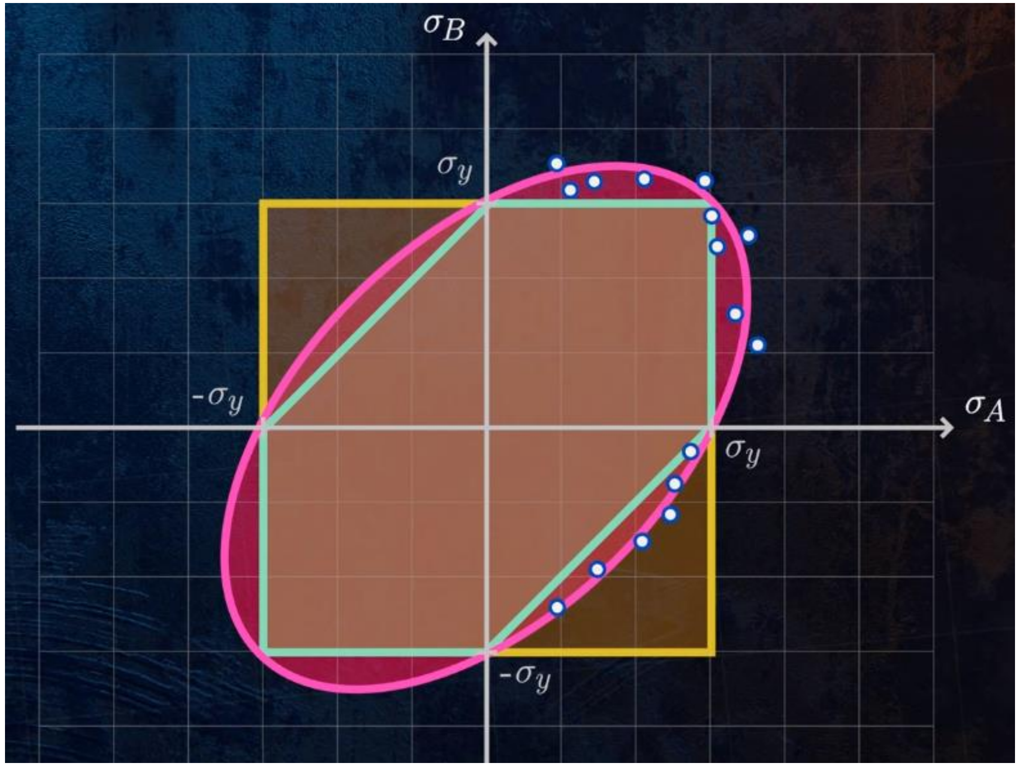
- Hidrostatik stress hacim değişimine sebep olan stress’tir
- Hidrostatik stressler ductile malzemelerde yielding’e sebep olmaz
- Yielding maksimum distortion energy uni-axial testteki yielding pointteki distortion energy’e eşit olduğunda başlar
- Ductile malzeme için deneysel datayla en uyumlu kırılma teorisidir.



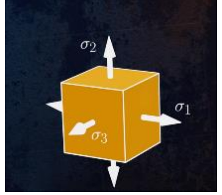
Triaxial stress

Stresses causing a change in volume

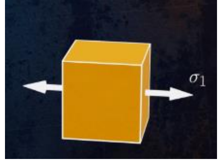
Stresses causing a distortion of shape



triaxial stress



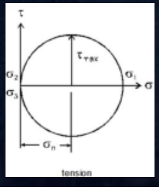
uniaxial stress



$$u_d = u_{d,y}$$

$$u_d = \frac{1+\nu}{6E}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]$$

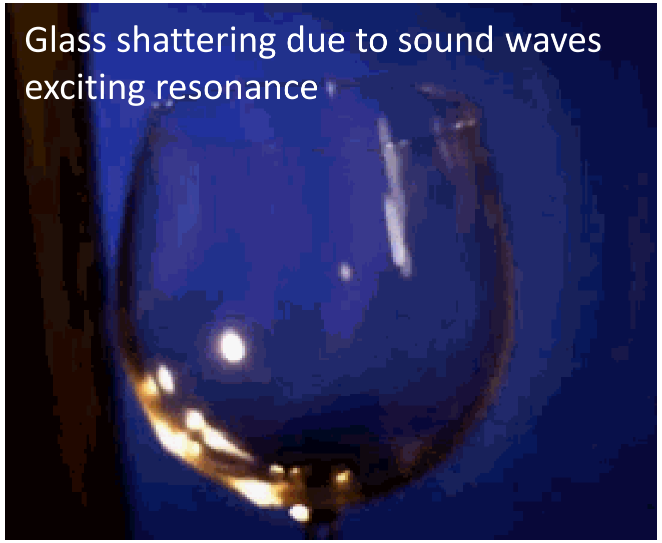
$$u_{d,y} = \frac{1+\nu}{3E}\,\sigma_y^2$$



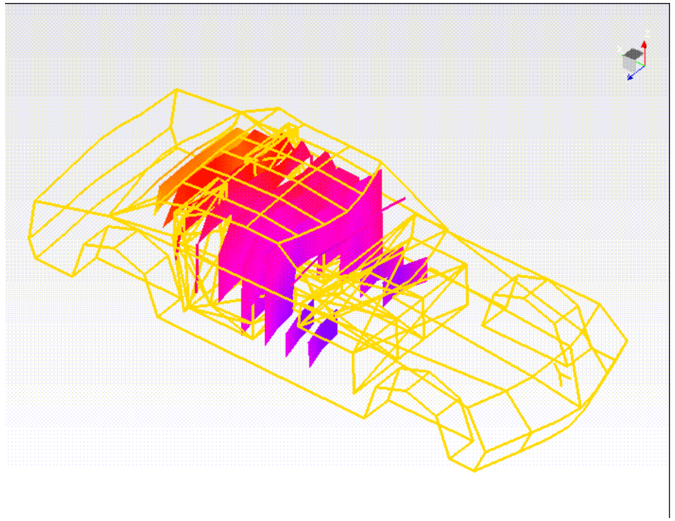
$$\underbrace{\sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]}}_{\text{equivalent von Mises stress } \sigma_{eq}} = \sigma_y$$

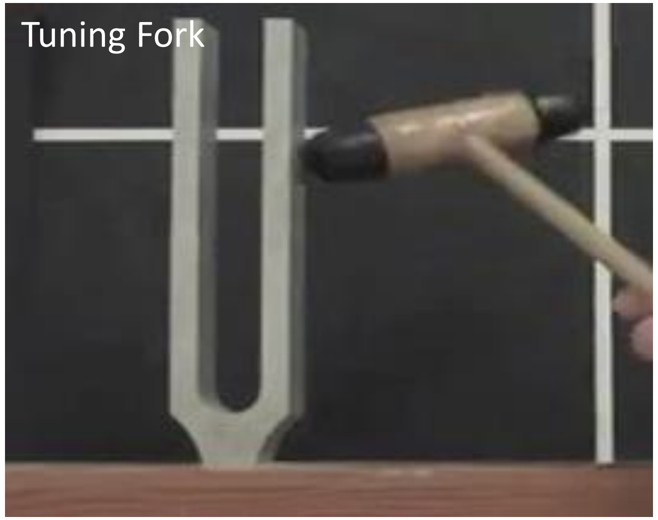
Resonance

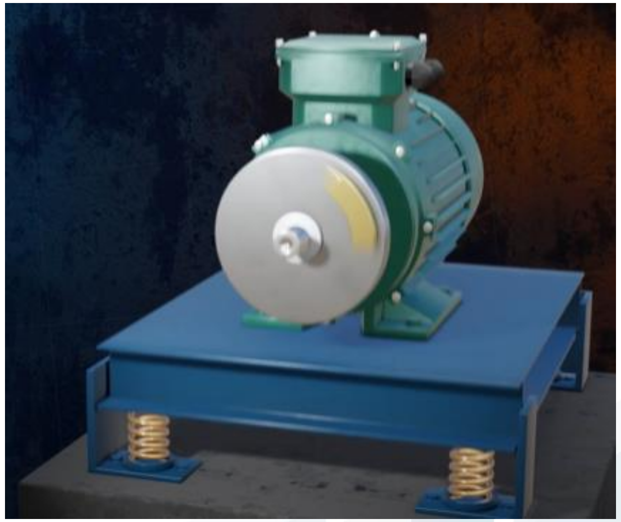

Flutter


Glass shattering due to sound waves exciting resonance

What is Resonance?

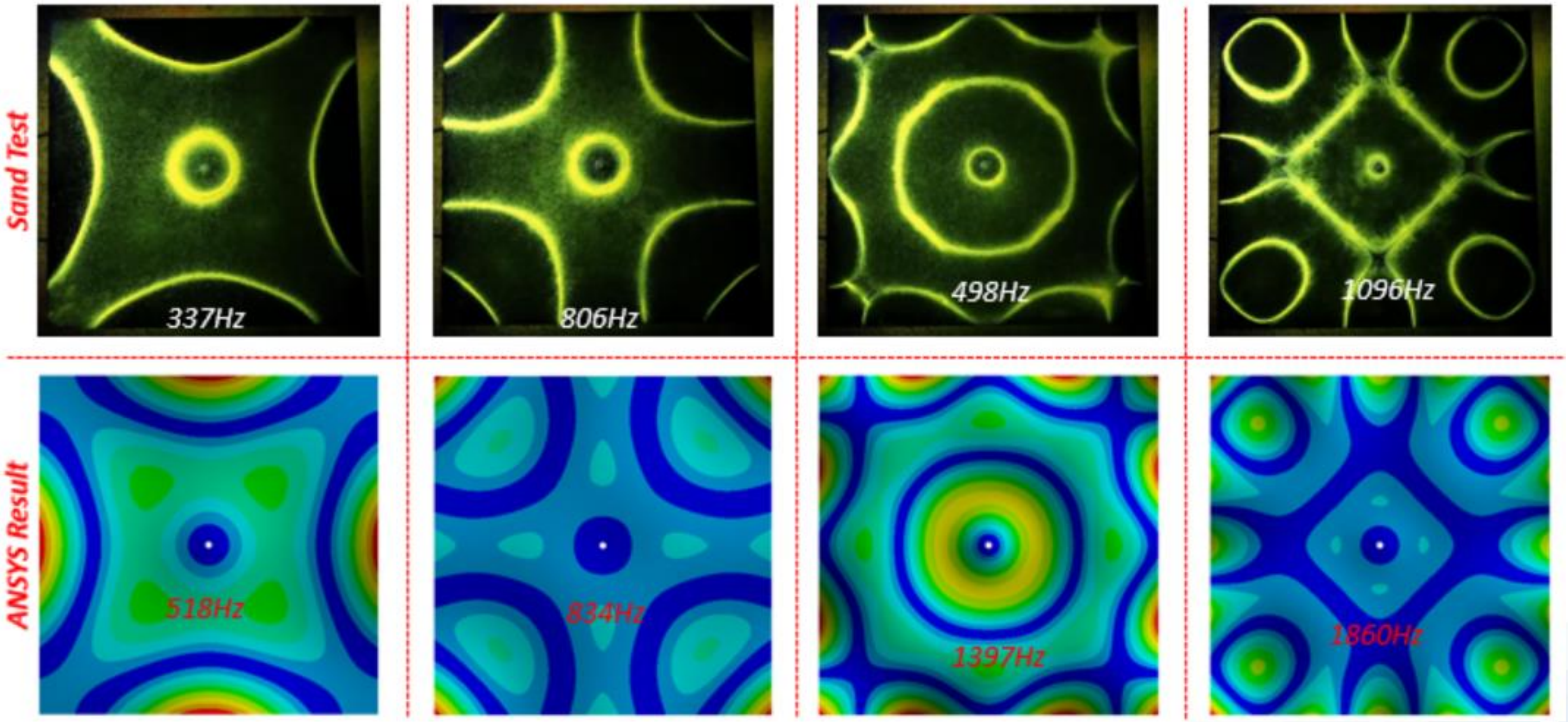



Tuning Fork



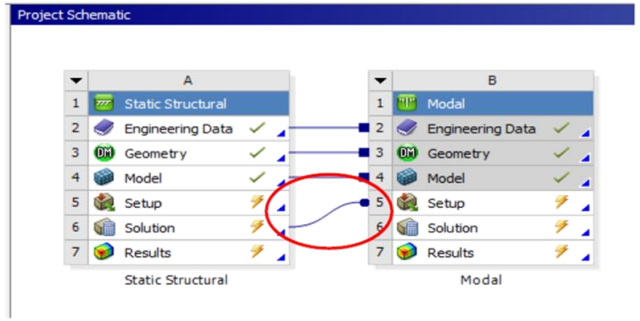
Modal Analysis

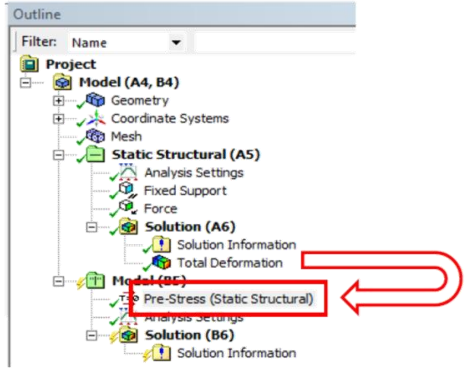
- Linear elastic material behavior is assumed. Small deflection theory is used
- No non-linear contact is allowed (All non-linear contacts are converted into a linear type of contact)
- The structure can be constrained or unconstrained
- Mode shapes are relative values, not absolute



Modal Analysis

Setup a pre-stressed modal analysis in the schematic by linking a static structural system to a modal system *at the solution level*.





Notice: in the modal system, the structural analysis result becomes an initial condition.

The stress state of a structure under influences the modal solution by modifying the stiffness of the structure:

$$[K]\{x_o\}=\{F\}$$

A linear static analysis is performed

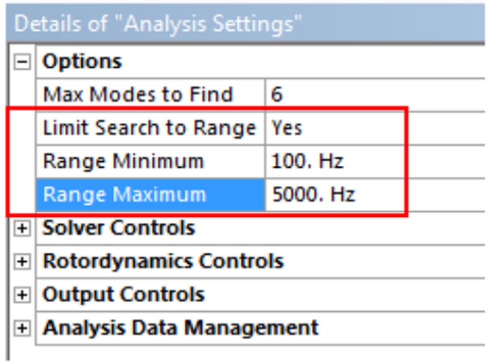
$$\Rightarrow$$

$$[\sigma_o]\rightarrow[S]$$

A stress stiffness matrix is calculated from the structural analysis

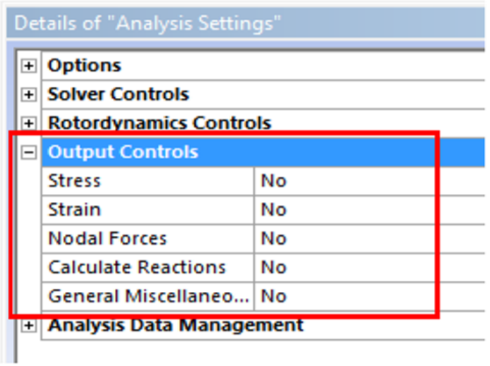
$$\left([K+S]-\omega_i^2[M]\right)\{\phi_i\}=0$$

The original free vibration equation is augmented to include the [S] term



Details of "Analysis Settings"

Options	
Max Modes to Find	6
Limit Search to Range	Yes
Range Minimum	100. Hz
Range Maximum	5000. Hz
Solver Controls	
Rotordynamics Controls	
Output Controls	
Analysis Data Management	



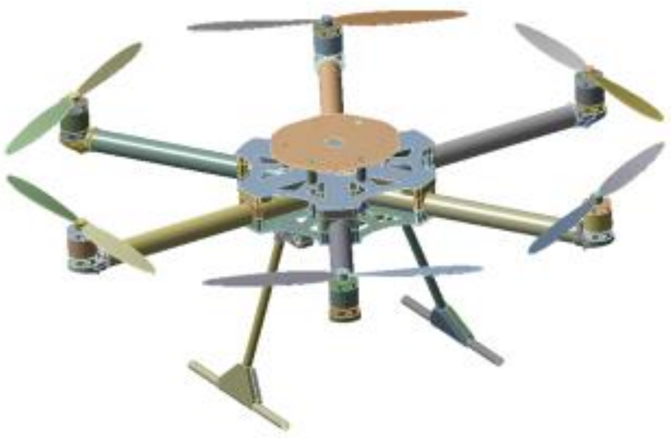
Details of "Analysis Settings"

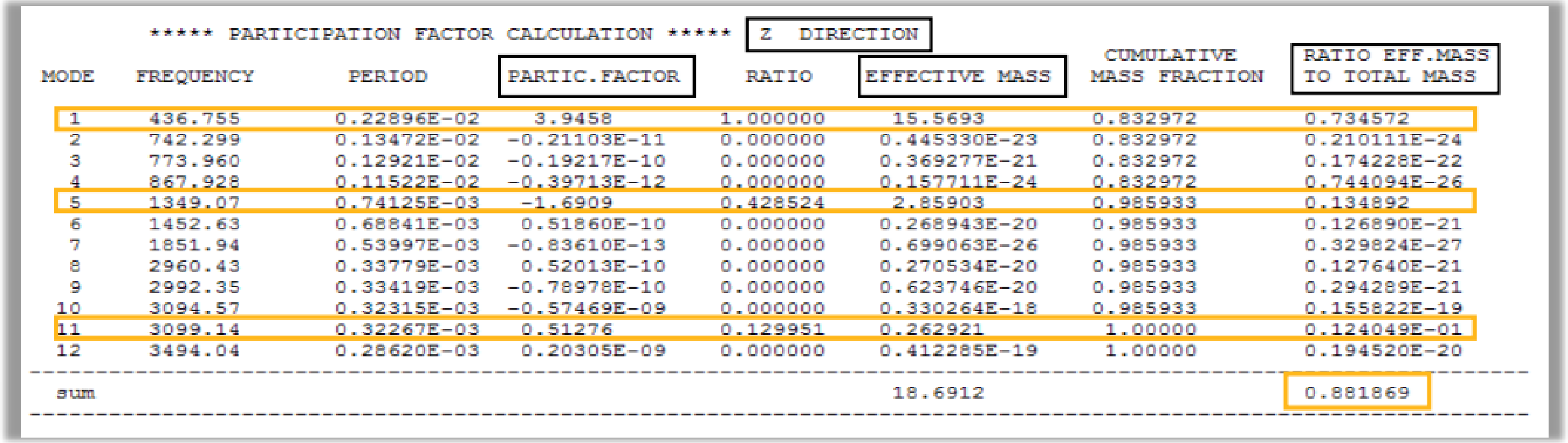
Options	
Solver Controls	
Rotordynamics Controls	
Output Controls	
Stress	No
Strain	No
Nodal Forces	No
Calculate Reactions	No
General Miscellaneo...	No
Analysis Data Management	

Modal Analysis

- Because of there is no excitation applied to the structure, the mode shapes are relative values not actual ones
- Mode shape results are mass normalized. The same situation is true for other results (stress, strain, etc.)
- Because of a modal result is based on the model’s physical properties and constraints, and not on any particular forcing inputs, we can predict where the maximum or minimum results will occur for a particular mode shape, but not the magnitudes of those results. Harmonic Analysis can do this job…

Kaç mode açacağız?





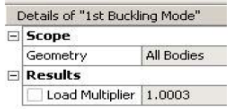
```
          ***** PARTICIPATION FACTOR CALCULATION *****  Z  DIRECTION
                                                                           CUMULATIVE     RATIO EFF.MASS
 MODE   FREQUENCY        PERIOD       PARTIC.FACTOR     RATIO     EFFECTIVE MASS   MASS FRACTION   TO TOTAL MASS

   1     436.755      0.22896E-02     3.9458        1.000000      15.5693        0.832972        0.734572
   2     742.299      0.13472E-02   -0.21103E-11    0.000000     0.445330E-23    0.832972        0.210111E-24
   3     773.960      0.12921E-02   -0.19217E-10    0.000000     0.369277E-21    0.832972        0.174228E-22
   4     867.928      0.11522E-02   -0.39713E-12    0.000000     0.157711E-24    0.832972        0.744094E-26
   5     1349.07      0.74125E-03    -1.6909        0.428524      2.85903        0.985933        0.134892
   6     1452.63      0.68841E-03    0.51860E-10    0.000000     0.268943E-20    0.985933        0.126890E-21
   7     1851.94      0.53997E-03   -0.83610E-13    0.000000     0.699063E-26    0.985933        0.329824E-27
   8     2960.43      0.33779E-03    0.52013E-10    0.000000     0.270534E-20    0.985933        0.127640E-21
   9     2992.35      0.33419E-03   -0.78978E-10    0.000000     0.623746E-20    0.985933        0.294289E-21
  10     3094.57      0.32315E-03   -0.57469E-09    0.000000     0.330264E-18    0.985933        0.155822E-19
  11     3099.14      0.32267E-03    0.51276        0.129951     0.262921         1.00000        0.124049E-01
  12     3494.04      0.28620E-03    0.20305E-09    0.000000     0.412285E-19     1.00000        0.194520E-20
----------------------------------------------------------------------------------------------------------------
  sum                                                             18.6912                        0.881869
----------------------------------------------------------------------------------------------------------------
```

Eigenvalue Buckling Analysis

- Lineer burkulma hesabı slenderness ratio>120 durumunda geçerlidir. Aksi takdirde iyimser, mühendislik anlamında kullanılması güç sonuçlar verecektir.
- Aşağıdaki kabullere göre çalışır
    - Lineer elastik malzeme davranışı
    - Small deflection teorisi
    - Lineerize edilmiş kontaklar
- Statik analize bağlanarak prestressed çözüm alınır, uygulanacak yük ve sınır koşulu statik analizde verilir.
- Analiz sonucu olarak yük çarpanı ve burkulma modları elde edilir. Kritik burkulma yükü uygulanan kuvvet ile yük çarpanının çarpımından elde edilir.

Statik analizde burkulmaya sebep olması beklenen yükün gerçek değeri uygulanırsa analiz sonucu elde edilen yük çarpanı doğrudan güvenlik katsayısı olacaktır.



Details of "1st Buckling Mode"

Scope	
Geometry	All Bodies
Results	
☐ Load Multiplier	1.0003

[buckling load] = λ * [actual load]

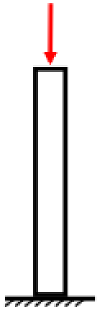
⇒ [buckling load]/[actual load] = λ = [safety factor]

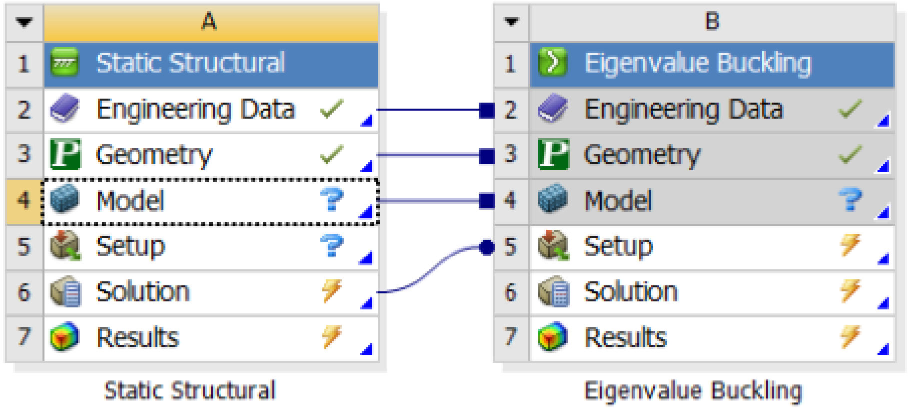
Buckling Modes

$$([K]+\lambda_i[S])\{\psi_i\}=0$$

Load Multiplier

F x λ = Buckling Load





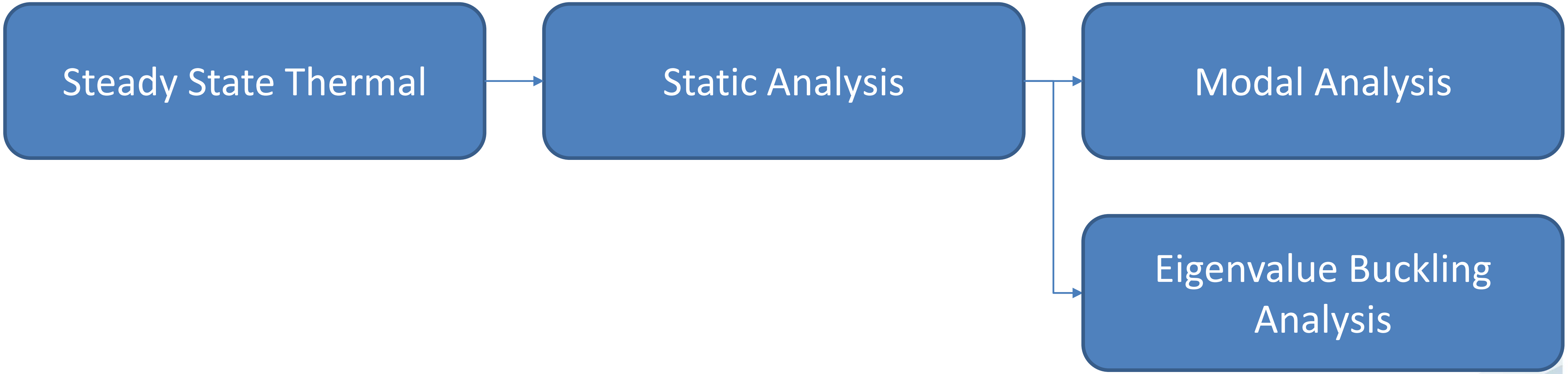
	A
1	Static Structural
2	Engineering Data ✓
3	Geometry ✓
4	Model ?
5	Setup ?
6	Solution ⚡
7	Results ⚡

Static Structural

	B
1	Eigenvalue Buckling
2	Engineering Data ✓
3	Geometry ✓
4	Model ?
5	Setup ⚡
6	Solution ⚡
7	Results ⚡

Eigenvalue Buckling

Uygulama



Steady State Thermal

Static Analysis

Modal Analysis

Eigenvalue Buckling Analysis

TUSAŞ MOTOR SANAYİİ A.Ş.
TUSAŞ ENGINE INDUSTRIES, INC.

GÜCÜN KAYNAĞI

TEŞEKKÜRLER