TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Aerodinamik ve Yanma Teknik Rehber

08.12.2022

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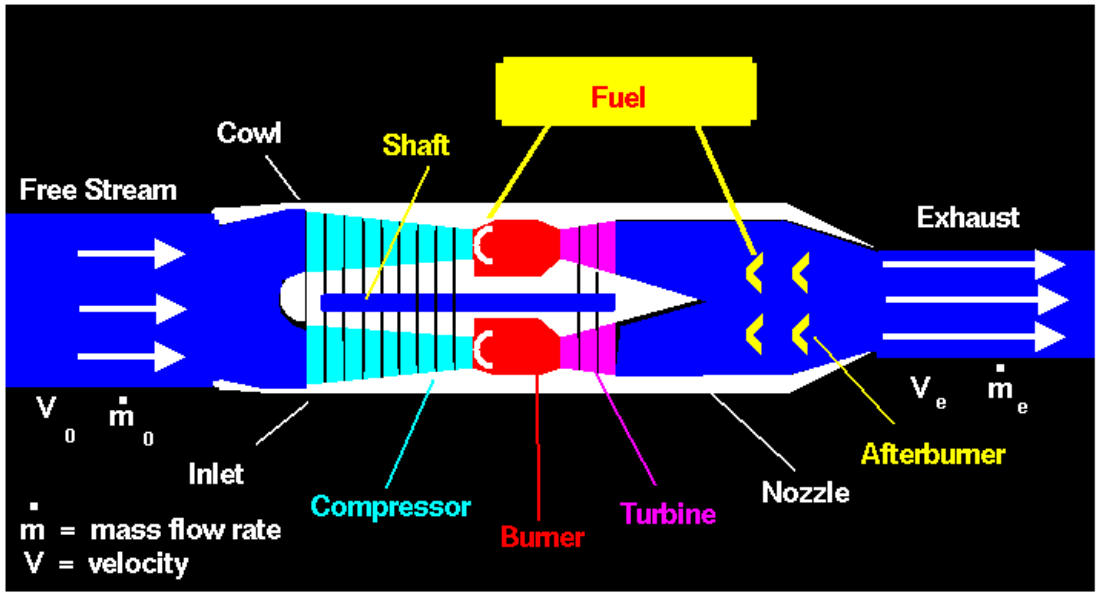
TASNİF DIŞI

AFTERBURNERS – INTRODUCTORY CONCEPTS

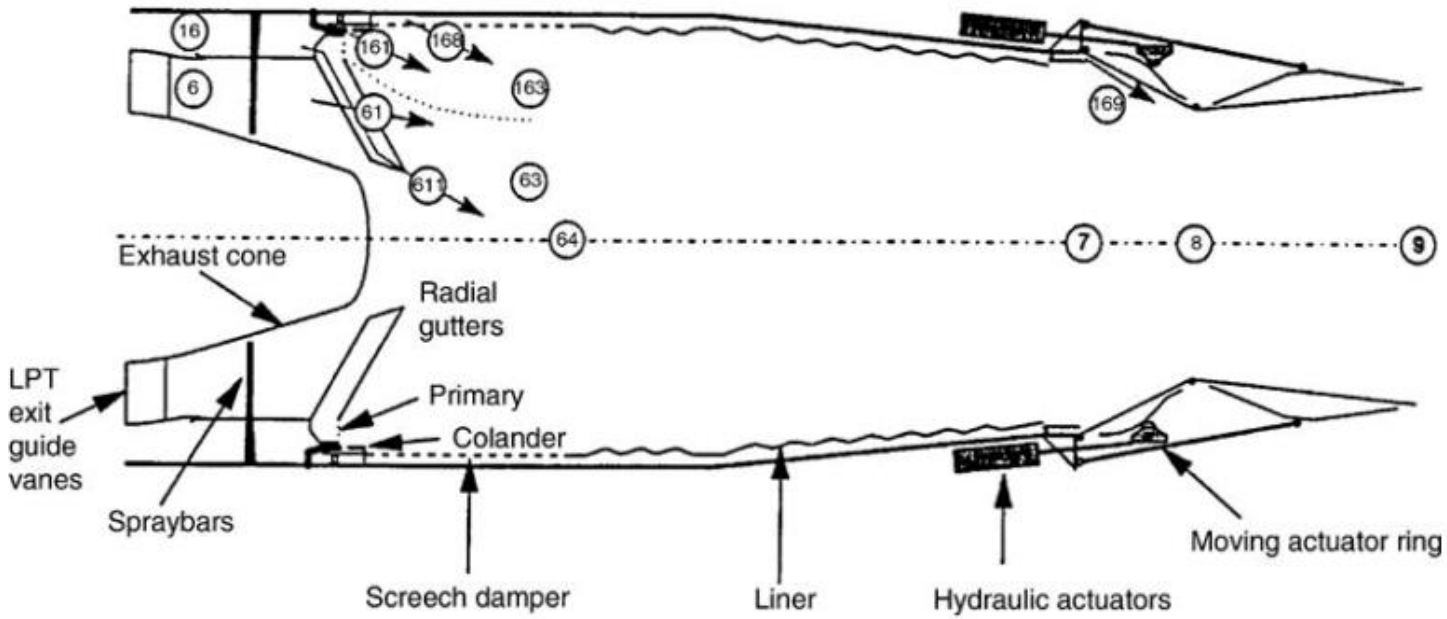
- Afterburners are used to produce more thrust while consuming a high amount of fuel.
- They are working for a short period of time for supersonic flight, combat and take-off.
- A schematic of a jet engine with an afterburner is shown below [1].
  - Afterburners are located between the turbine and exhaust 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.



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

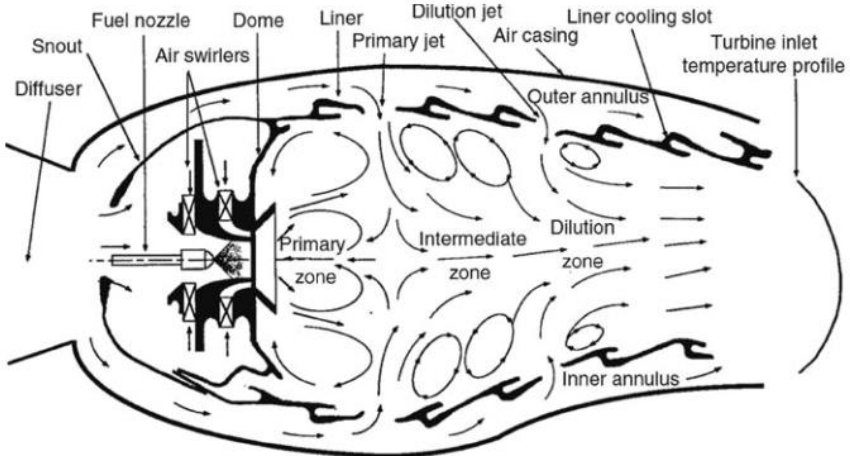
AFTERBURNERS – INTRODUCTORY CONCEPTS

- 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.

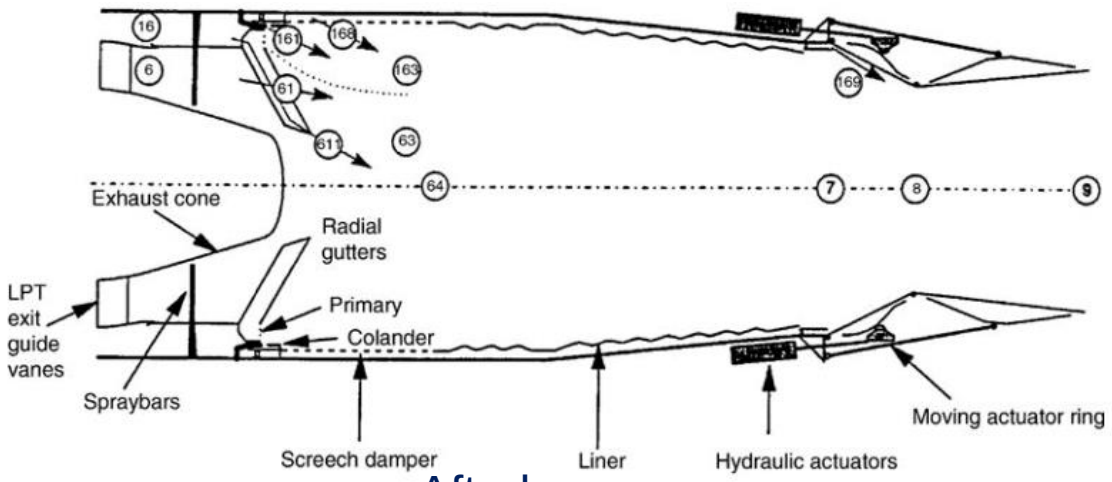


AFTERBURNERS – INTRODUCTORY CONCEPTS

- 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.



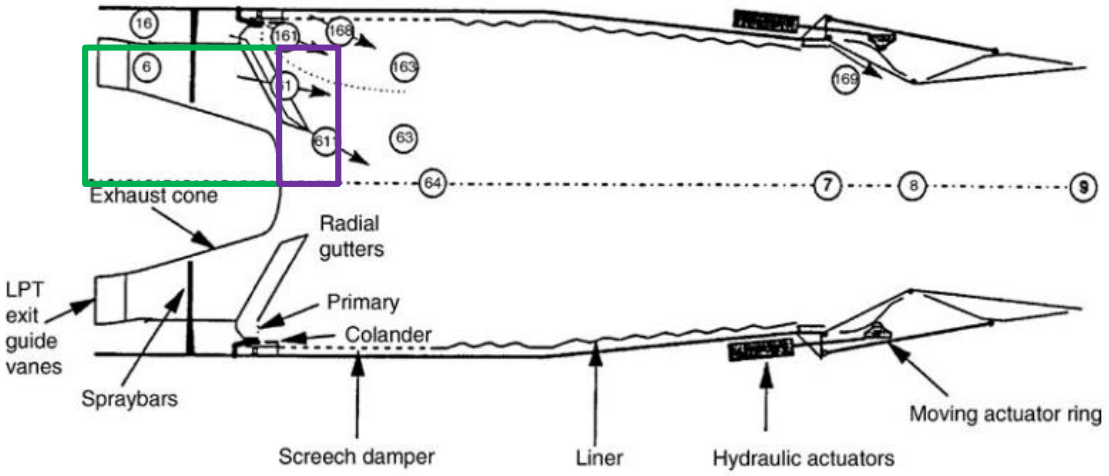
Combustion chamber

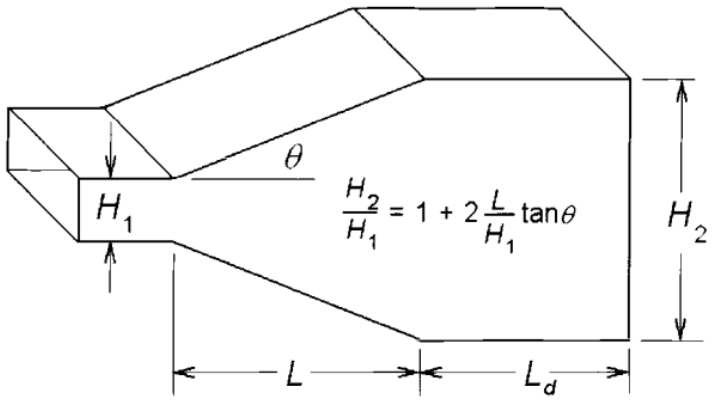


Afterburner

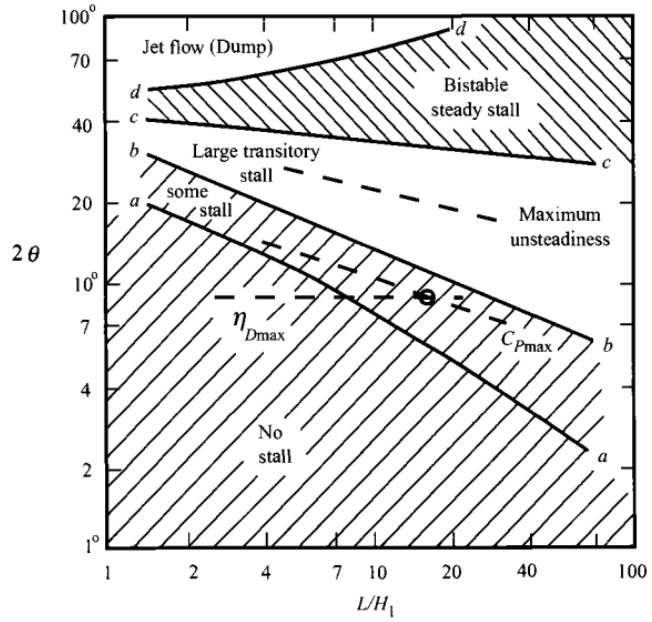
AFTERBURNERS – Components- Diffuser

- 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.





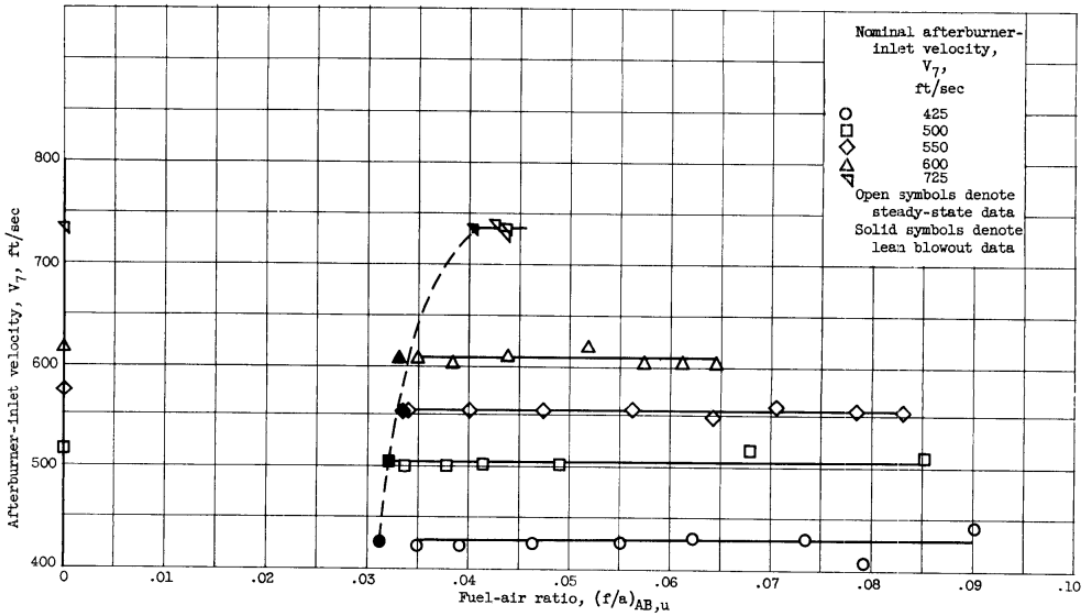
Diffuser



Diffuser stability Map

AFTERBURNERS – Components- Diffuser

- 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 inlet velocity effect on the blow-out limits of an afterburner is shown [5] below.
- The main purpose of the diffuser is reducing the inlet velocity, and participants can design their diffuser regarding such experimental data.
- In addition to resoruce books, using such experimental data will provide bonus points to the participants.



(c) Afterburner-inlet velocity and lean blowouts.

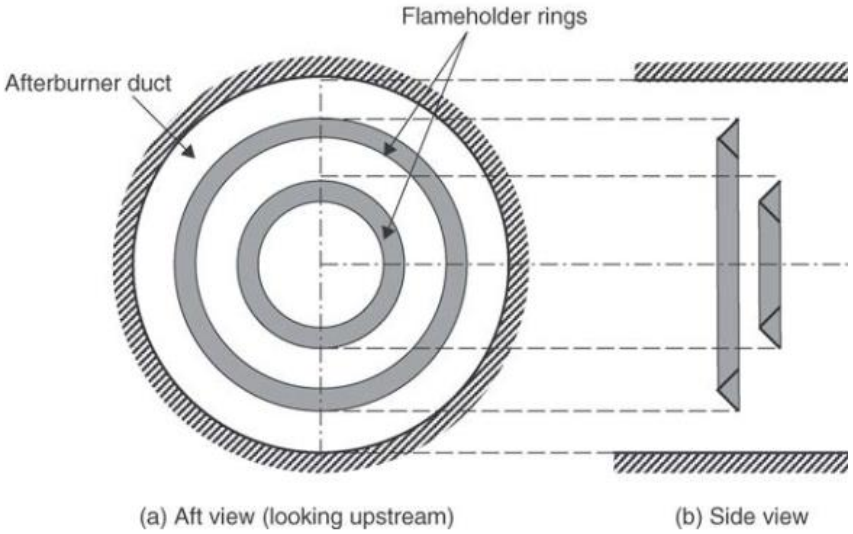
AFTERBURNERS – Components- V-Gutters

- Flame stabilization is one of the most important part of the combustion.
- Inherently, the flow velocity is higher than the flame propagation speed and results with the blowout.
- The blowout means that the flame physically leaves the combustion chamber or afterburner.
- To prevent this issue, flame is needed to be anchored.
- The blowout is simply function of combustion chamber loading which is the ratio of chemical kinetic time to residence time.
- Chemical kinetic time refers how much time requires for reaction
- Residence time characterizes the time which the reactants reside in the reaction zone
- If $\tau_{res} < \tau_{che}$ $\longrightarrow$ blow-off
- We need to increase the residence time or faster combustion to prevent blow-off.
- This is called as flame anchoring.

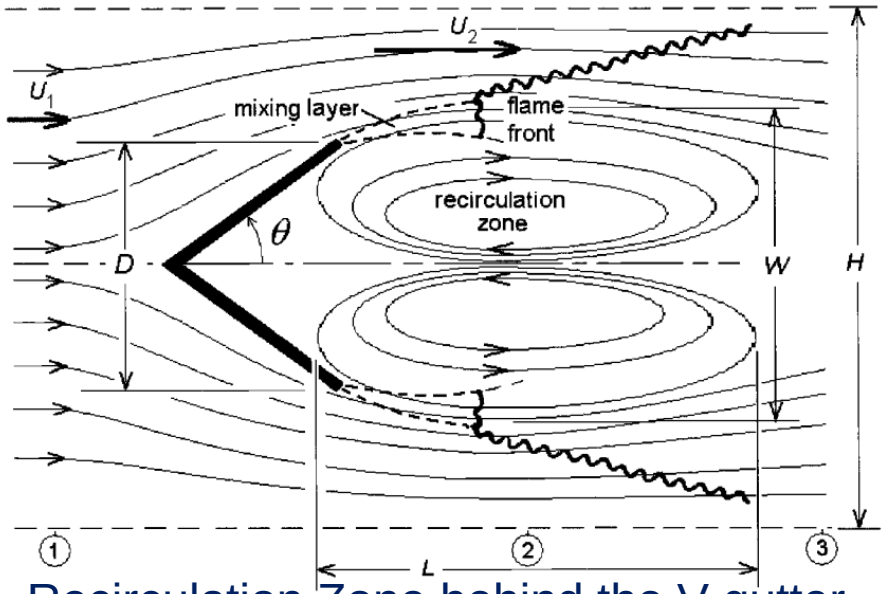
$$Loading = {}^{\tau_{che}}/_{\tau_{res}}$$

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.



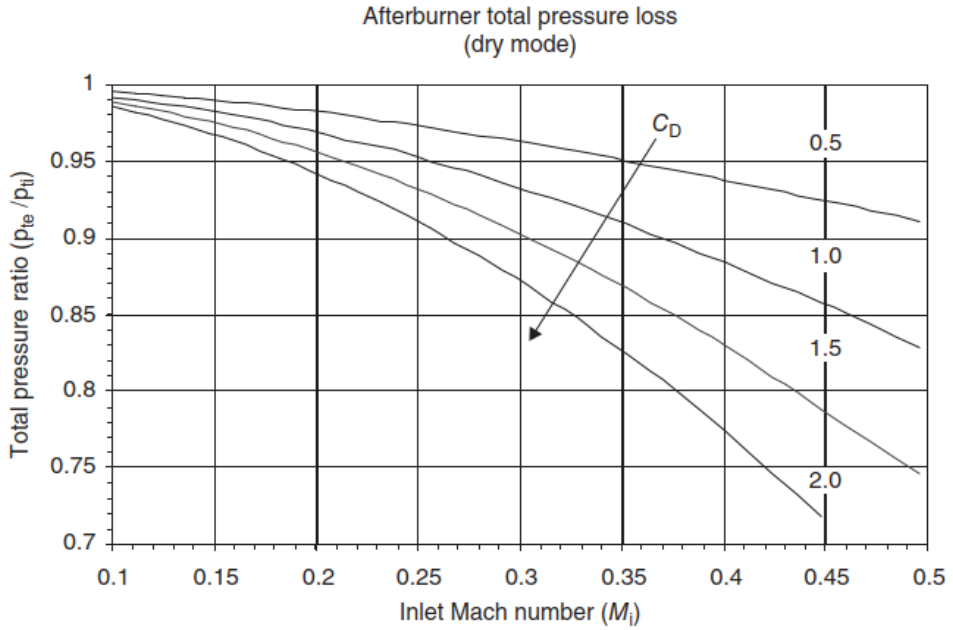
A schematic of the V-gutter

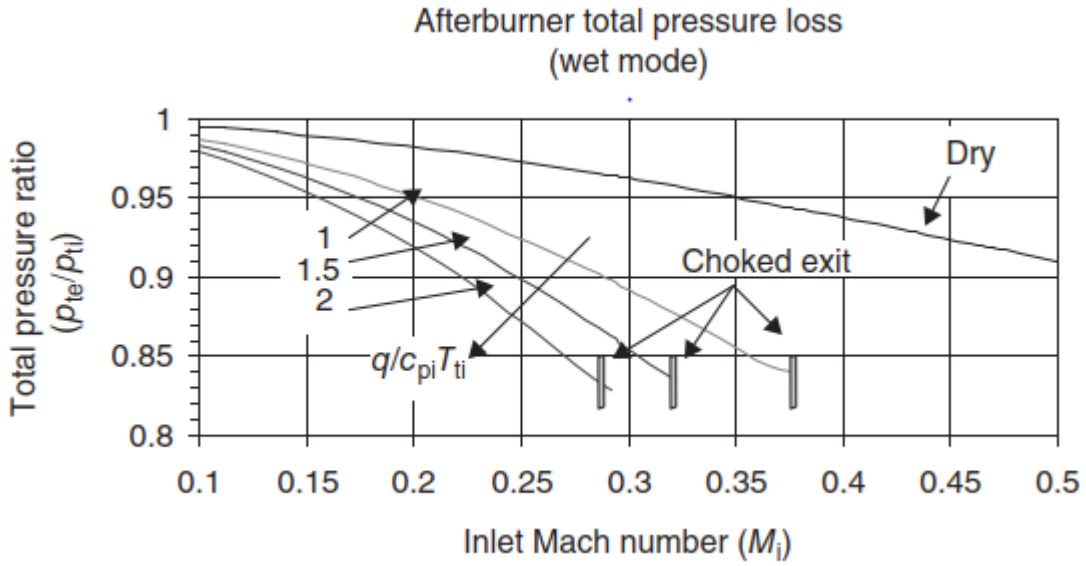


Recirculation Zone behind the V-gutter

AFTERBURNERS – Components- V-Gutters

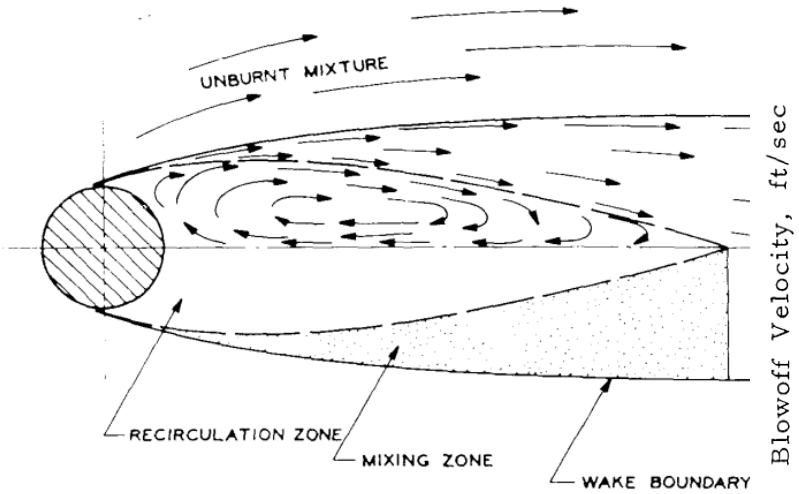
- One of the main issue of the V-gutters is to create blockage to the flow. If blockage is increased, it leads higher drag coefficient (Cd) and total pressure loss.
- A representative pressure loss due to V-gutters is shown below [3]. Participants must keep in their mind that, the V-gutters still exist 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.

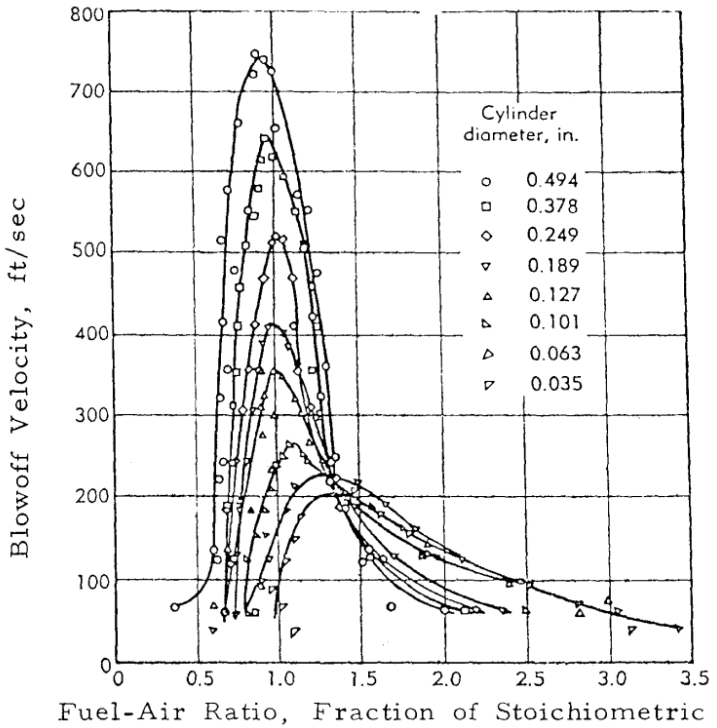


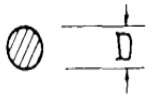


AFTERBURNERS – Components- V-Gutters

- 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

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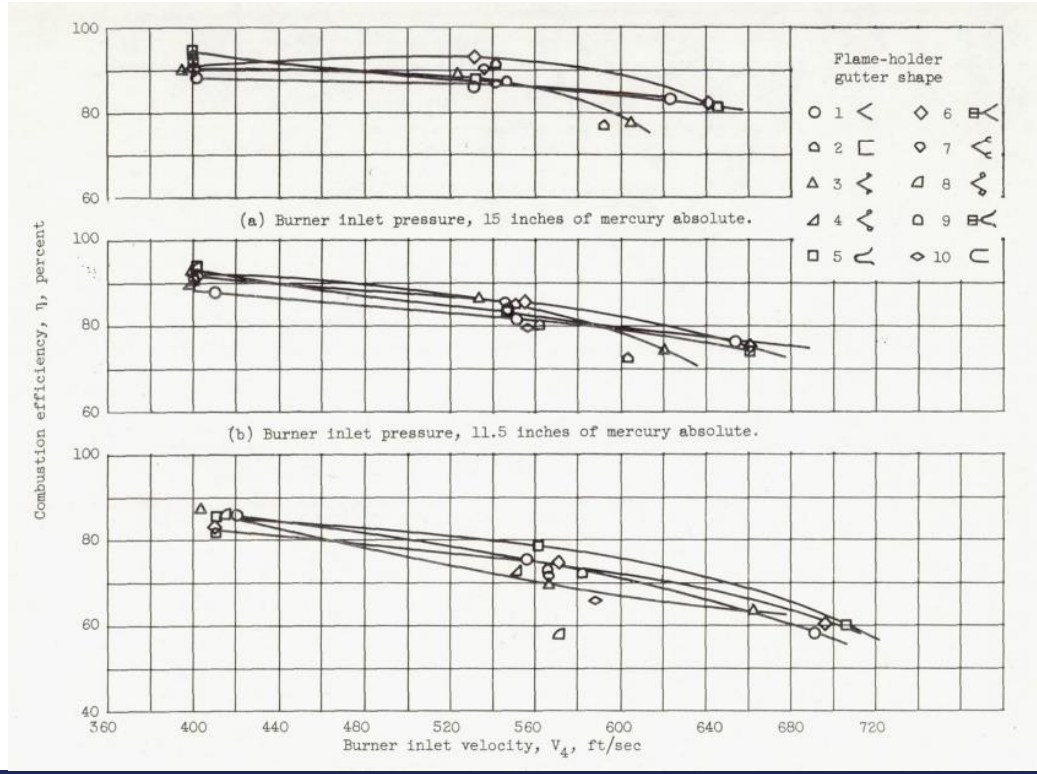
  5- Afterburners, details can be found in the References section
- In addition, NASA NTRS server has a lots of details about afterburners. For example, an experimental investigation of the various V-gutter shapes on the combustion efficiency is shown [7] below.
- In addition to resource books, using such experimental data will provide bonus points to the participants.

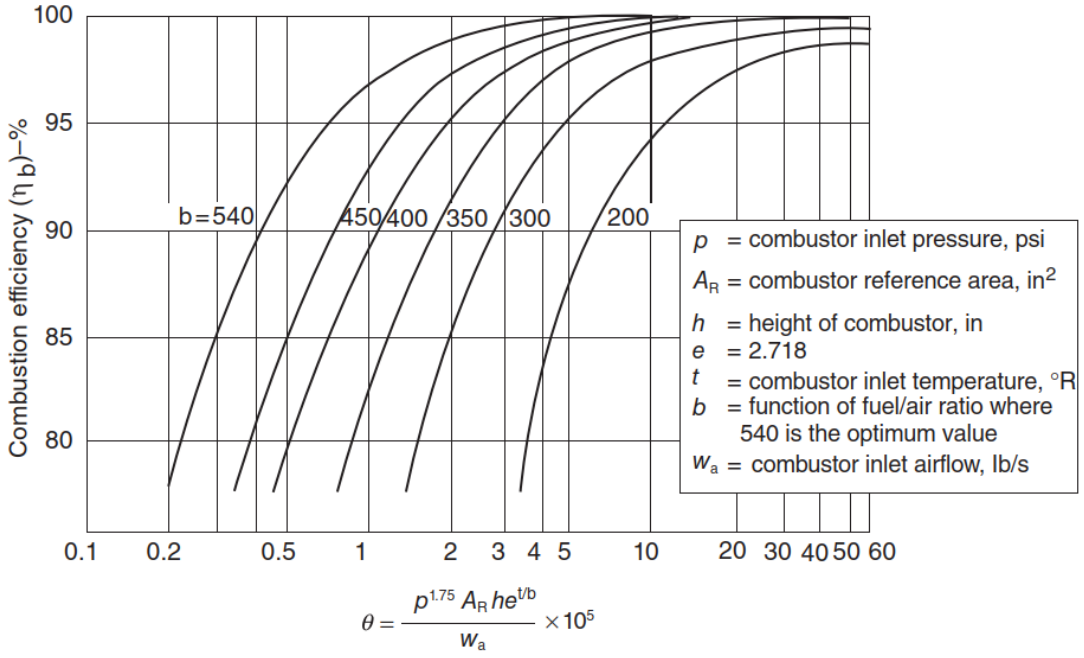


AFTERBURNERS – Components- Liners

- 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:

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

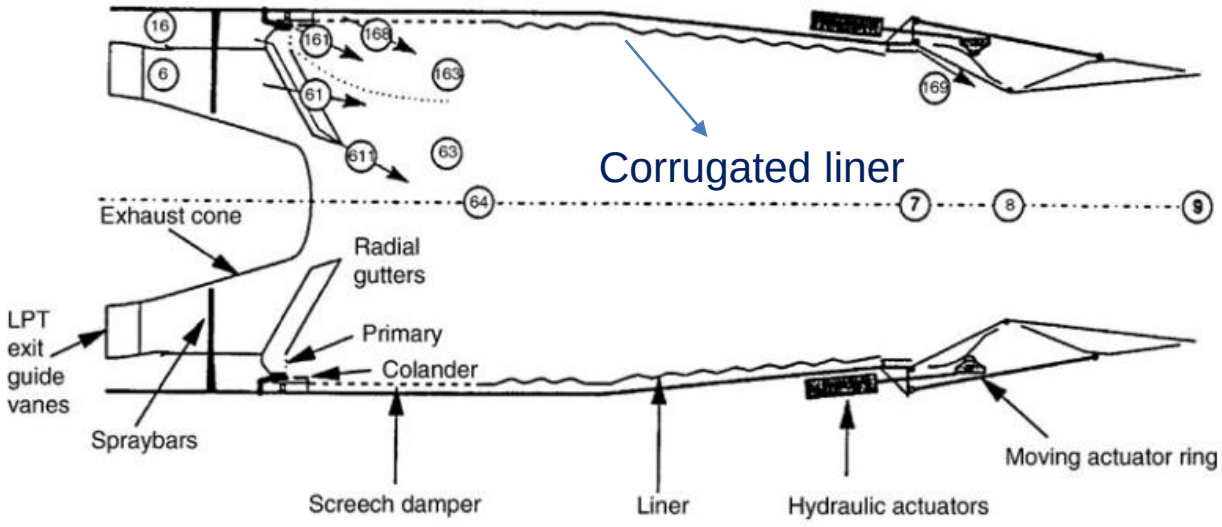
- p and t represents the afterburner intake pressure and temperature, respectively. $\dot{m}$ is the afterburner mass flow rate, A_R is the reference cross section area of the afterburner h is the radius of the afterburner.
- However, longer afterburner requires more coolant mass flow rate and it makes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

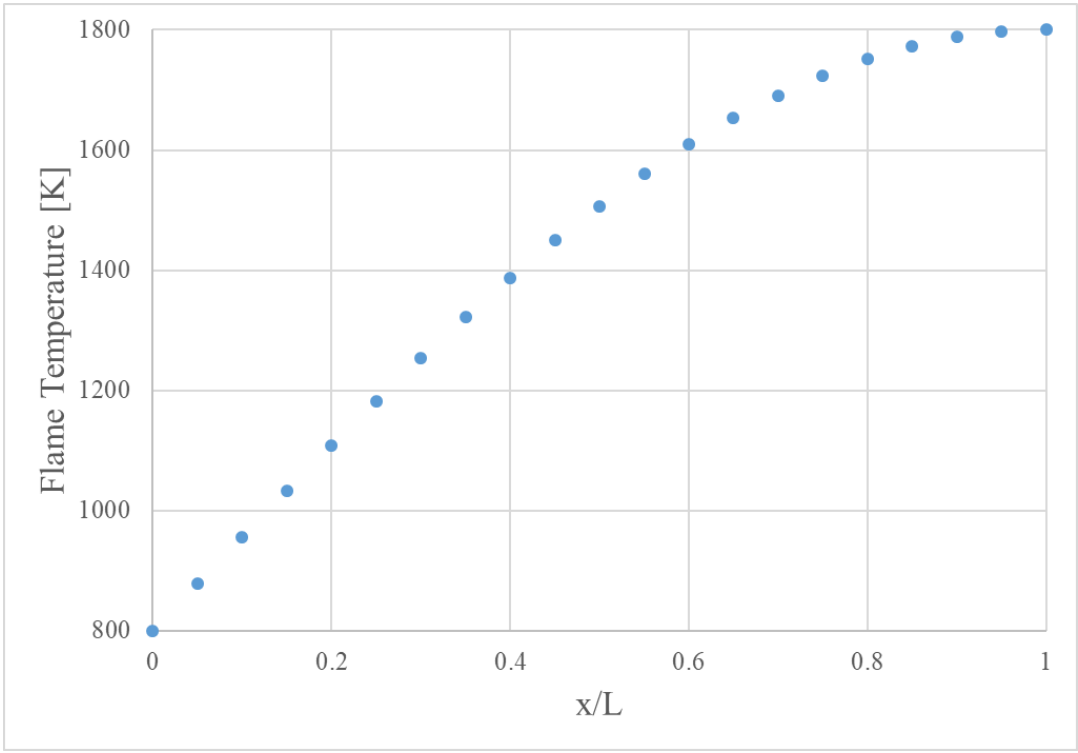


AFTERBURNERS – Components- Liners

- 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

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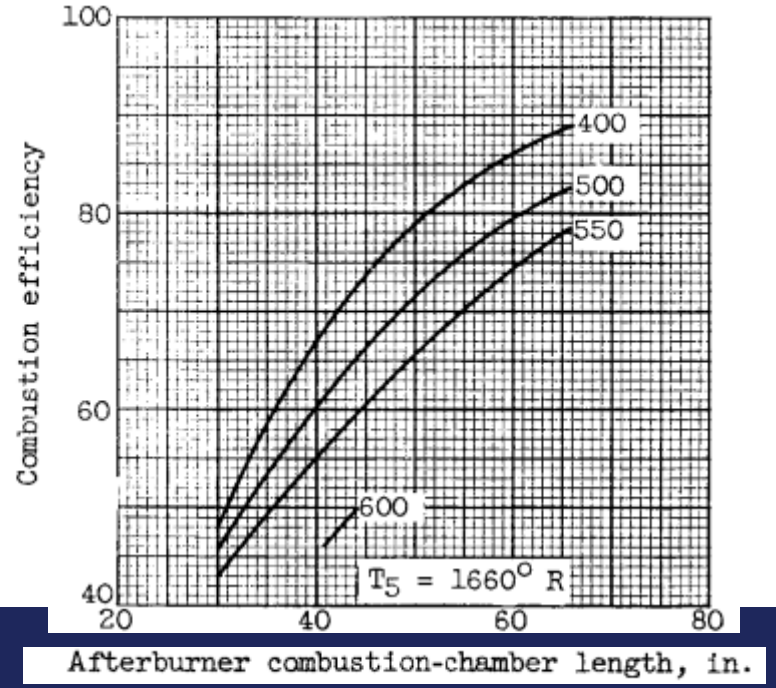
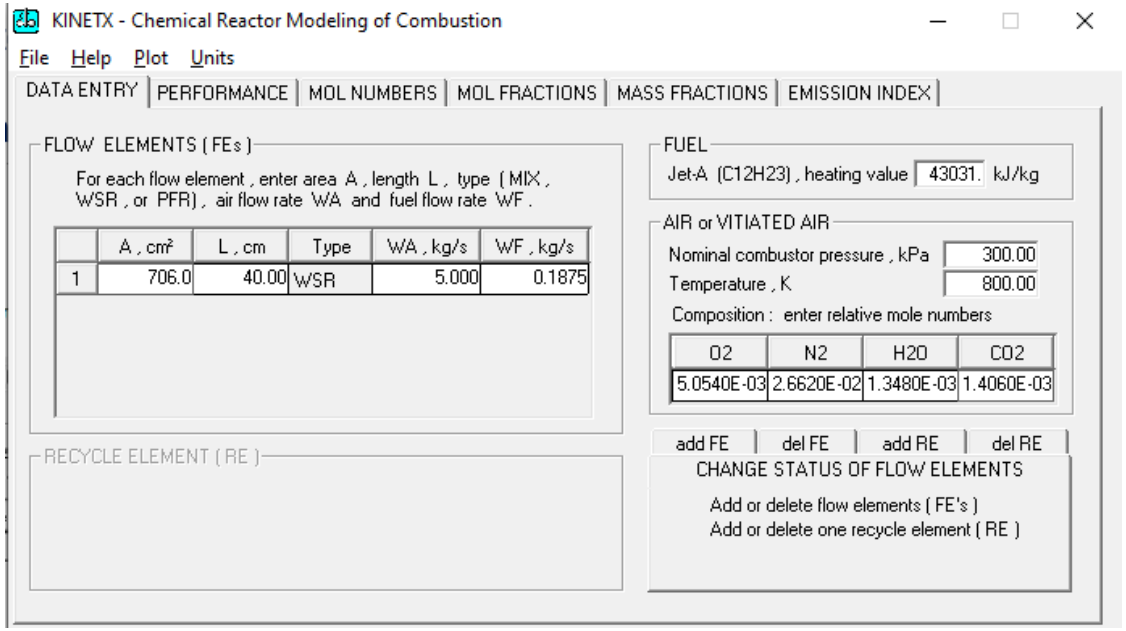
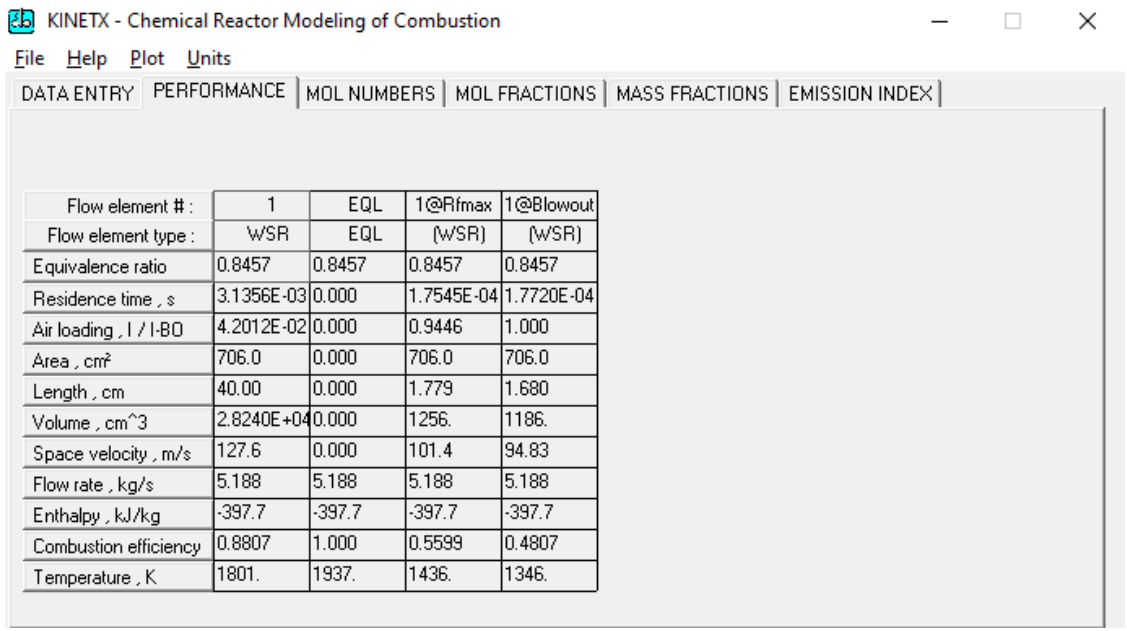
- In addition, NASA NTRS server has a lots of details about afterburners. For example, an experimental investigation of the effect of the afterburner length on the combustion efficiency is shown [5] below. It is obviosly seen that, the longer afterburner leads higher combustion efficiency.
- Also, the 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.





References

[1] https://www.grc.nasa.gov/www/k-12/airplane/turbab.html Access Date: 25.11.2022
[2] https://www.rolls-royce.com/products-and-services/defence/aerospace/combat-jets/ej200.aspx Access Date: 25.11.2022
[3] Aircraft Propulsion, Second Edition, Saeed Farokhi, Wiley, 2014
[4] Aircraft Engine Design, Third Edition, Jack D. Mattingly, William H. Heiser, David T. Pratt, Keith M. Boyer and Brenda A. Haven, AIAA Education Series, 2018
[5] Experimental Investigation of Effects of Combustion-chamber Length and Inlet Total Temperature, Total Pressure, and Velocity on Afterburner Performance, Charles King, NACA Research Memorandums, 1957
[6] Afterburners, E. Zukoski, , Aerothermodynamics of Aircraft Engine Components, edited by G. C. Oates, AIAA, New York, 1985, pp. 47–144.
[7] An Investigation of Effects of Flame-Holder Gutter Shape on Afterburner Performance, S. Nakanishi, W. Velie and L. Bryant, NACA Research Memorandums, 1954
[8] Empirical Cooling Correlation for an Experimental Afterburner With an Annular Cooling Passage, William K. Ko£fel and Harold R. Kaufman, NACA Research Memorandums, 1952

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

GÜCÜN KAYNAĞI

TEŞEKKÜRLER

TASNİF DIŞI

TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Mekanik Tasarım ve Aksesuar Teknik Rehber
08.12.2022

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TASNİF DIŞI

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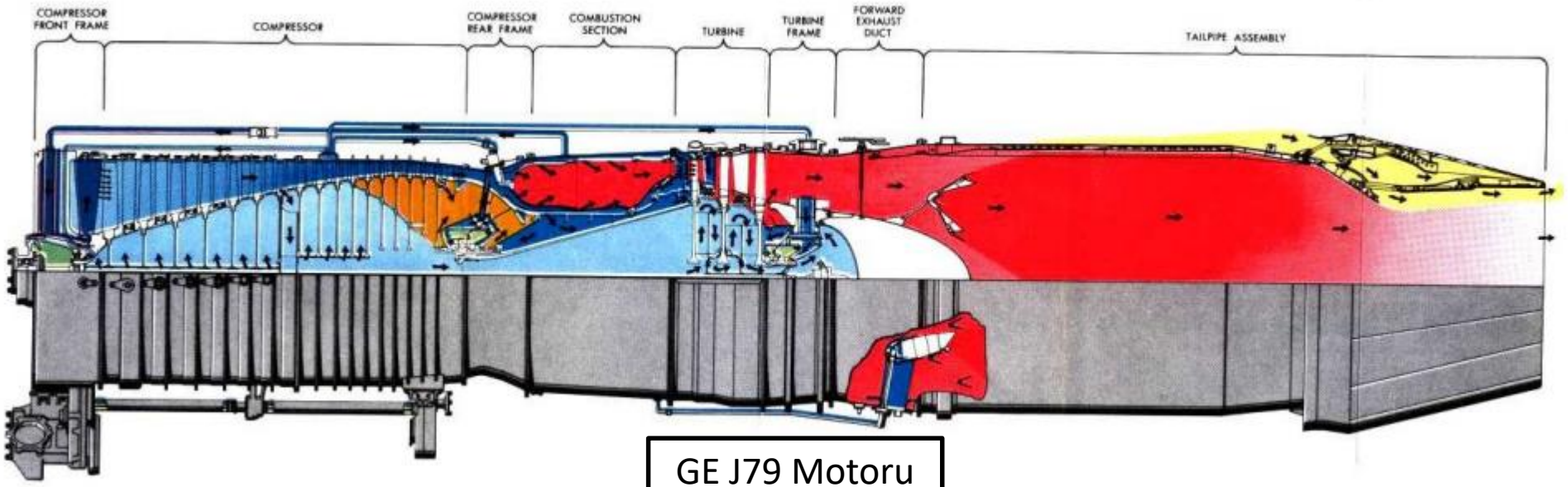
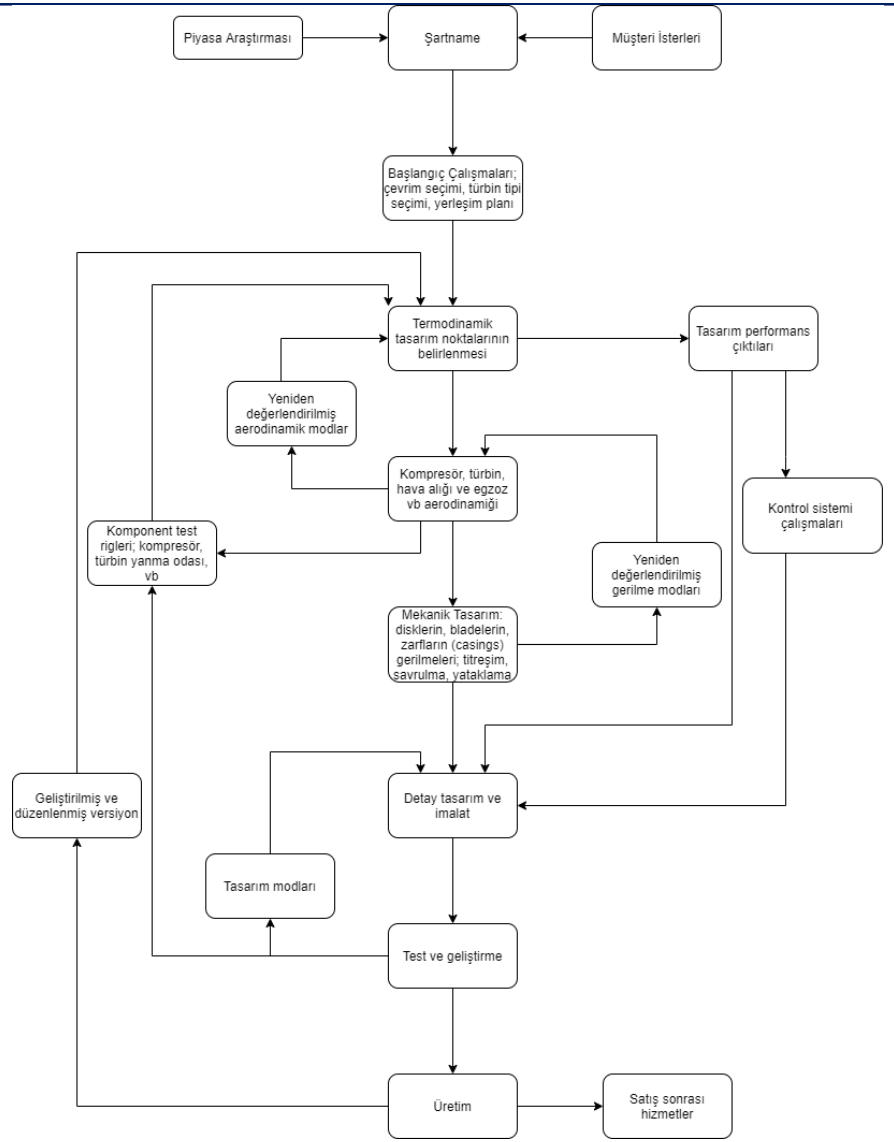


GE J79 Motoru

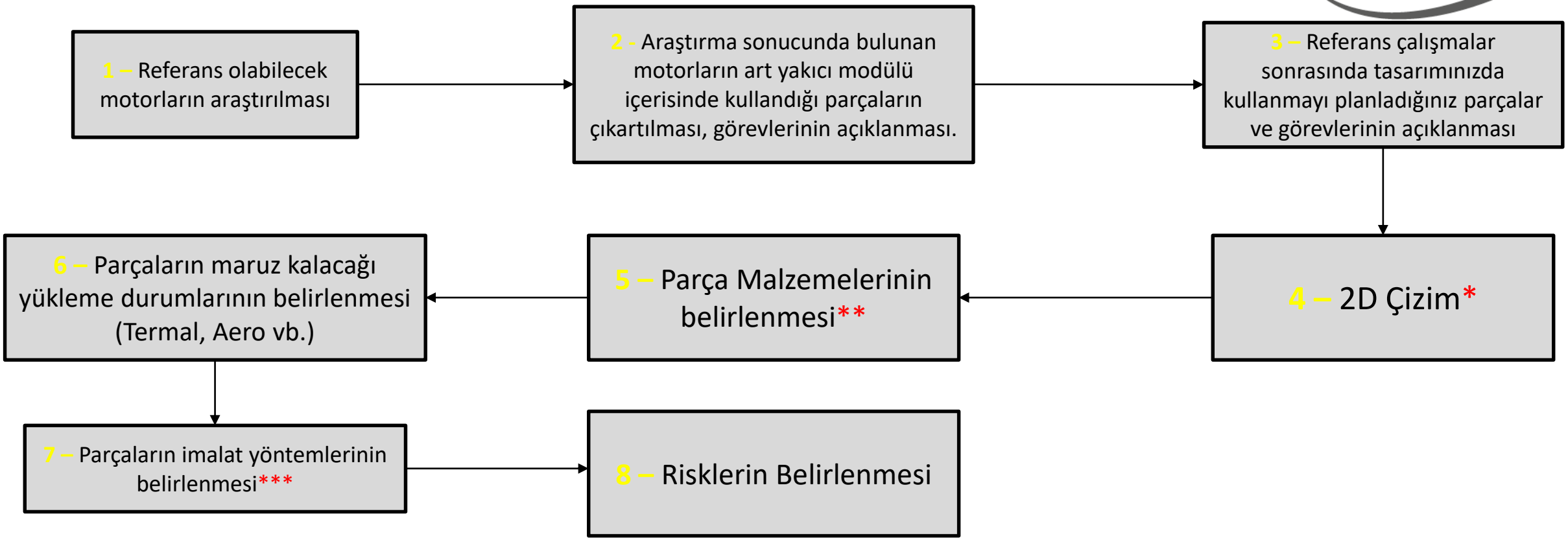
TEKNOFEST Havacılık, Uzay ve Teknoloji Festivali (TEKNOFEST) Teknoloji Yarışmaları kapsamında düzenlenen Jet Motor Tasarım Yarışması'nda bir turbojet motor için art yakıcı modülünün kavramsal tasarımının gerçekleştirilmesi amaçlanmaktadır. Yarışmaya katılacak olan takımlardan beklenen, şartnamede belirtilmiş olan Tasarım kriterlerine uygun şartları sağlayabilecek bir art yakıcı, çekirdek motorun arka kısmına entegre edilecek aerodinamik geçiş bölümü ve çıkış egzoz nozül bölümlerinin kavramsal tasarımını yapmak ve tasarım raporunu hazırlamaktır.

Örnek Gaz Türbin Motor Tasarım Aşamaları



Gas Turbine Theory, 7th Edition, Saravanamuttoo et al.

Art Yakıcı (Afterburner) – Kavramsal Tasarım Raporu



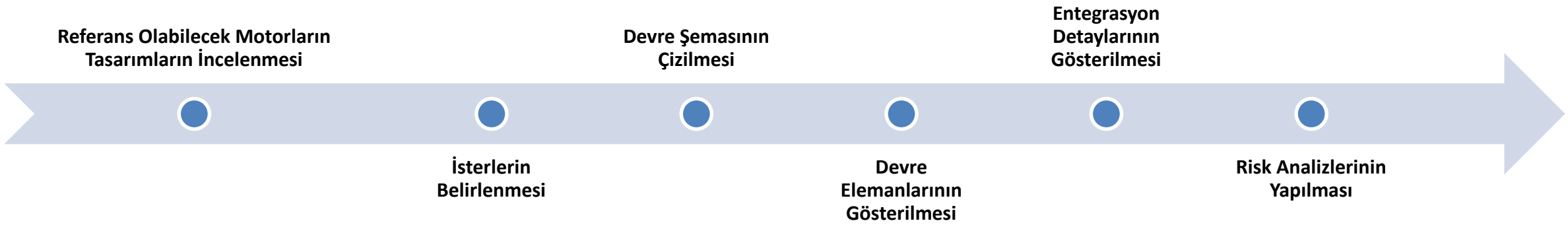
Yukarıda örnek bir akış şeması belirtilmiştir.

* 2D Çizim aşamasında şartnamede belirtilen boyut kısıtları göz önünde bulundurularak değerlendirilecektir.

** Malzeme Seçimi esnasında nelere dikkat edildiği Kavramsal Tasarım Raporunda (KTR) açıklanmalıdır. (Sıcaklık, E/ρ vb.)

*** Maliyet analizi yapılması beklenmektedir.

Parçaların Belirlenmesi



- İsterlerin belirlenmesi: Şartnamede verilen isterlere göre ilerlenecektir.
- Devre Şeması: Tasarımda kullanılan elemanların ve görevlerinin tanımlandığı şemadır.
- Devre Elemanlarının Gösterilmesi : Tasarımda kullanılan elemanların özelliklerinin tabloda gösterildiği kısımdır.
- Entegrasyon Detayları: Tasarımda kullanılan elemanların entegrasyon detaylarının gösterildiği kısımdır (imalatı, arayüzleri ve montajı).
- Risk Analizi: Yapılan tasarımda ortaya çıkabilecek olası hatalar ve bu hataların çözümlerinin sunulduğu çalışmadır. Bu çalışma ile Detay Tasarım Raporu (DTR) aşamasında olabilecek olası değişiklikler açıklanmaktadır.

*** Yapılan seçimlerin nedenleriyle açıklanması özgünlük açısından önemli olacaktır ve raporda beklenmektedir.**

Malzeme Seçimi

Malzeme	Yoğunluk	Maksimum Çalışma Sıcaklığı	Akma Dayanamı	Çekme Dayanımı	Karakteristik Özelliği
Malzeme 1					
Malzeme 2					
Malzeme 3					

Malzeme seçimi esnasında bu tarz bir tablo ile karılaştırma yapılabilir. Malzeme veri tabanı için örnek sayfa: https://asm.matweb.com

Değerlendirme kriterleri olarak aşağıdaki maddeler örnek olarak verilebilir:

*Maksimum Çalışma Sıcaklığı *Akma Dayanımı *Çekme Dayanımı *İşlenebilirlik-Kullanım durumuna göre kaynaklanabilirlik

*Oksidasyon direnci *Kütle yoğunluğu *Ulaşılabilirlik

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

TEŞEKKÜR EDERİZ

TASNİF DIŞI

TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Malzeme Teknik Rehber
08.12.2022

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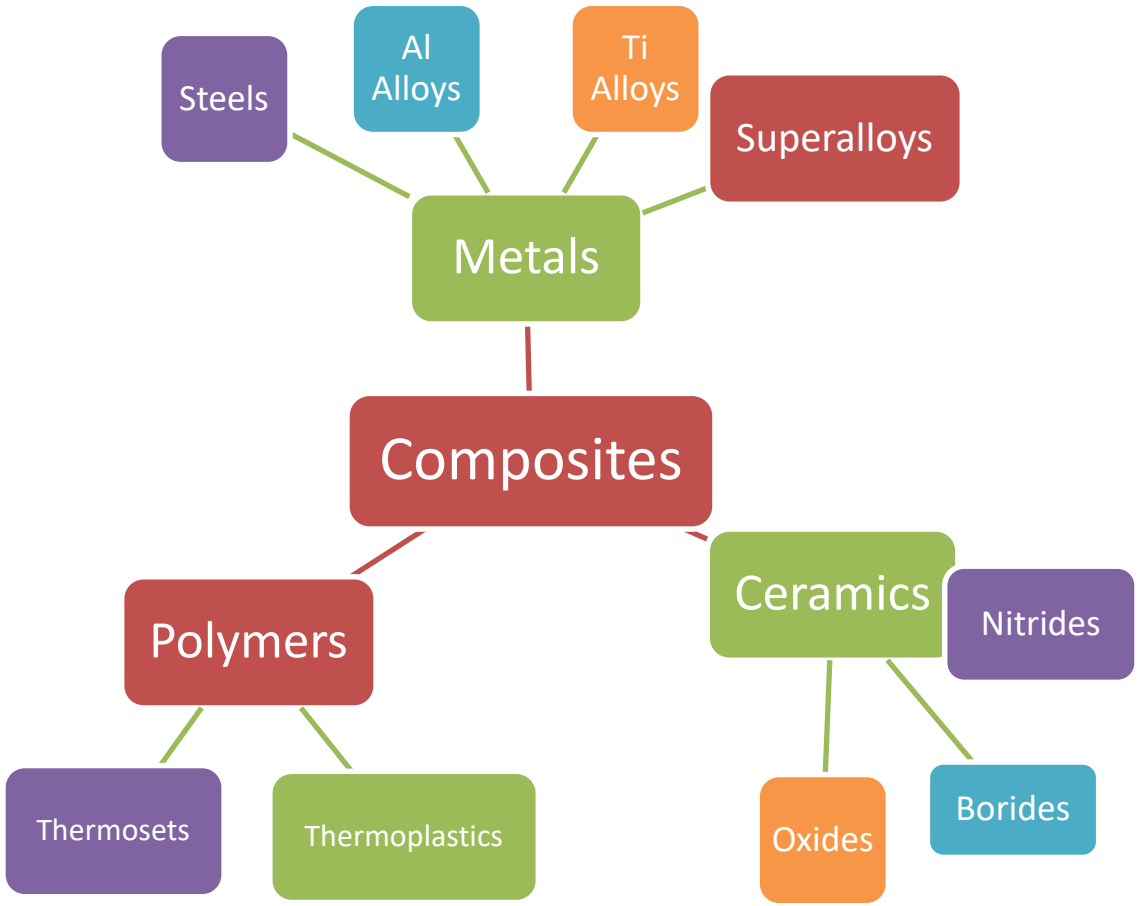
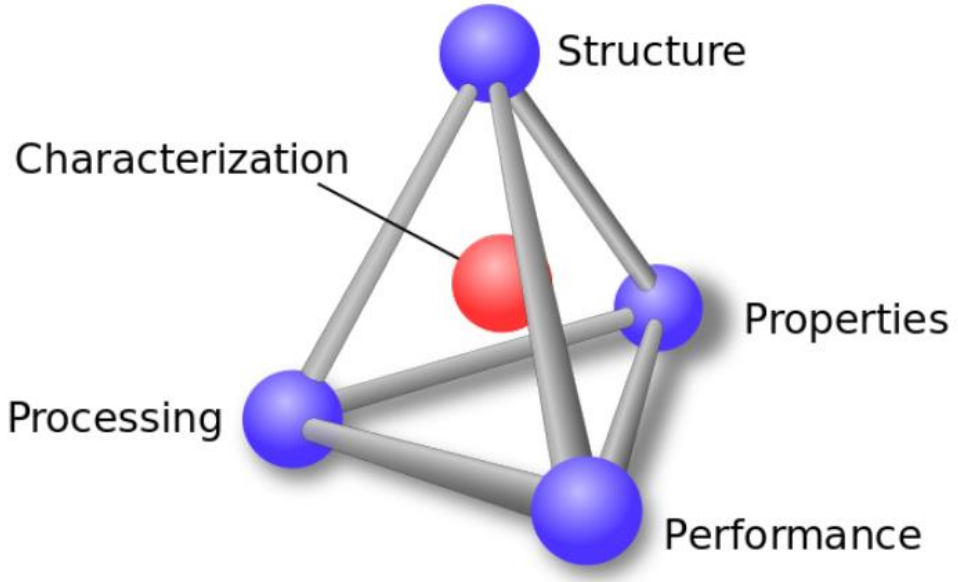
TASNİF DIŞI

MATERIALS

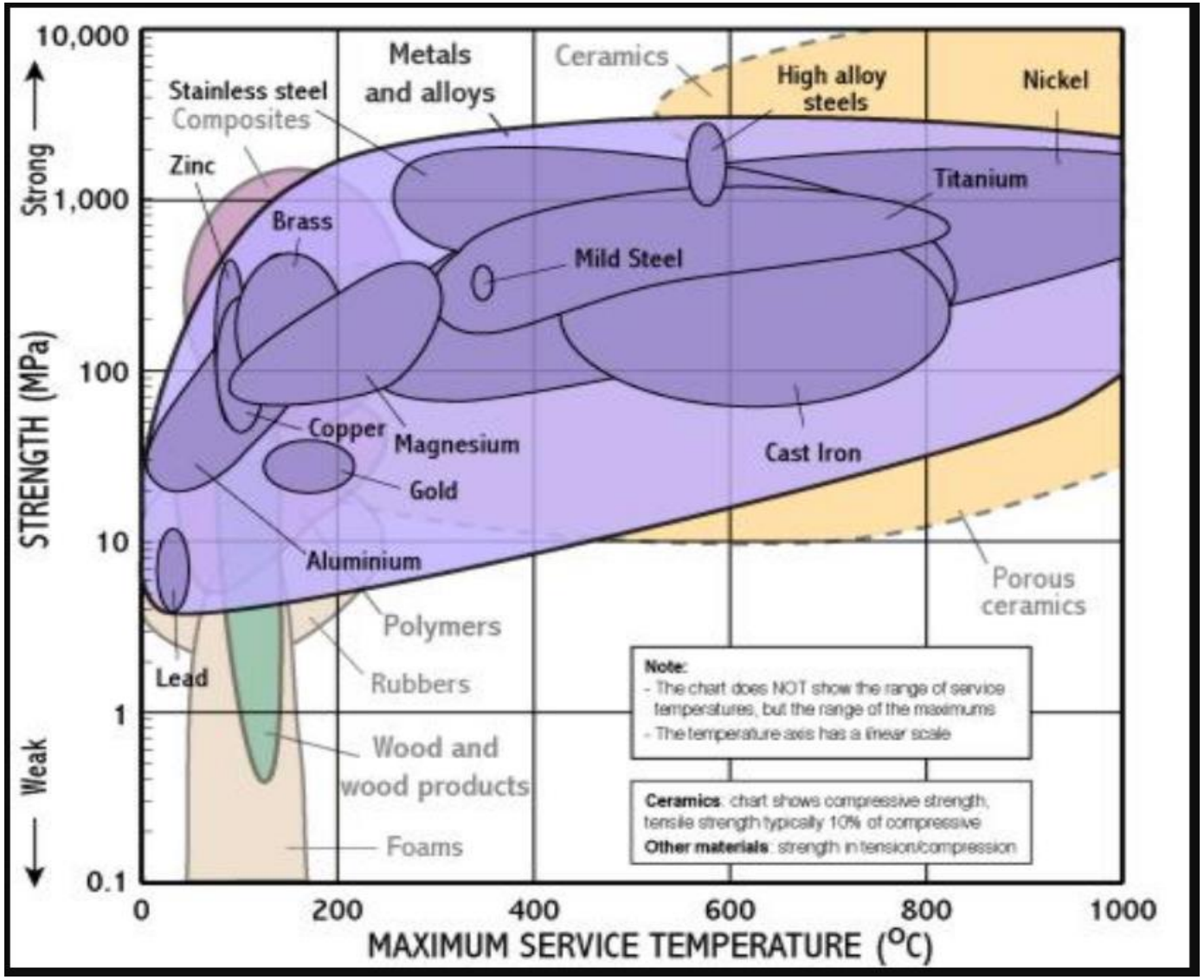




Material cost, performance, processing, properties, structure characteristics shall be considered during material selection.

TASNİF DIŞI

MATERIALS



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

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

An example of Ashby diagrams that can be used during materials selection

TASNİF DIŞI

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.
- nonferromagnetic, a property of importance in the electrical and electronics industries.
- 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.
- has an attractive appearance in its natural finish, which can be soft and lustrous or bright and shiny. It can be virtually any color or texture.
- Some aluminum alloys exceed structural steel in strength

Aluminum alloys can be used in compressor and fan sections, if temperature and stress requirements are satisfied.

TASNİF DIŞI

ALUMİNIUM AND ALUMİNIUM 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

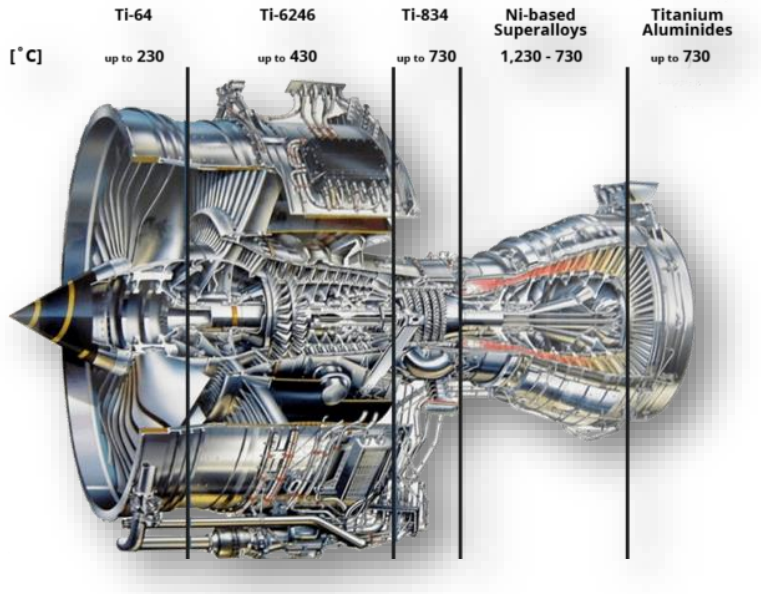
- 1xx.x Controlled unalloyed (**pure**) compositions
- 2xx.x **Copper** principal alloying element
- 3xx.x **Silicon** principal alloying element but **Cu** and **Mg** are specified
- 4xx.x **Silicon** principal alloying element
- 5xx.x **Magnesium** principal alloying element
- 7xx.x **Zinc** principal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

TASNİF DIŞI

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.).



Cross section through a Trent 900 aero engine, Rolls Royce

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.**

Ti alloys can be selected for the parts that work low and medium temperature

TASNİF DIŞI

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

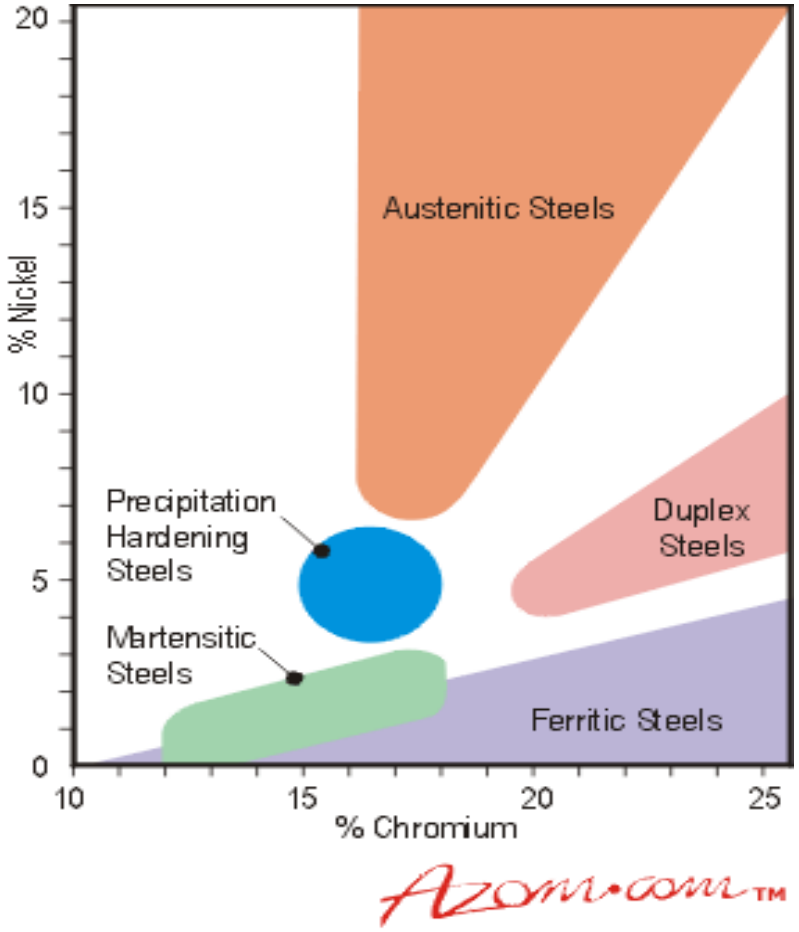
Materials selection shall be make based on the requirements of the parts

Parts such as compressor blades, impellers, fan can be produced from titanium alloys

TASNİF DIŞI

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

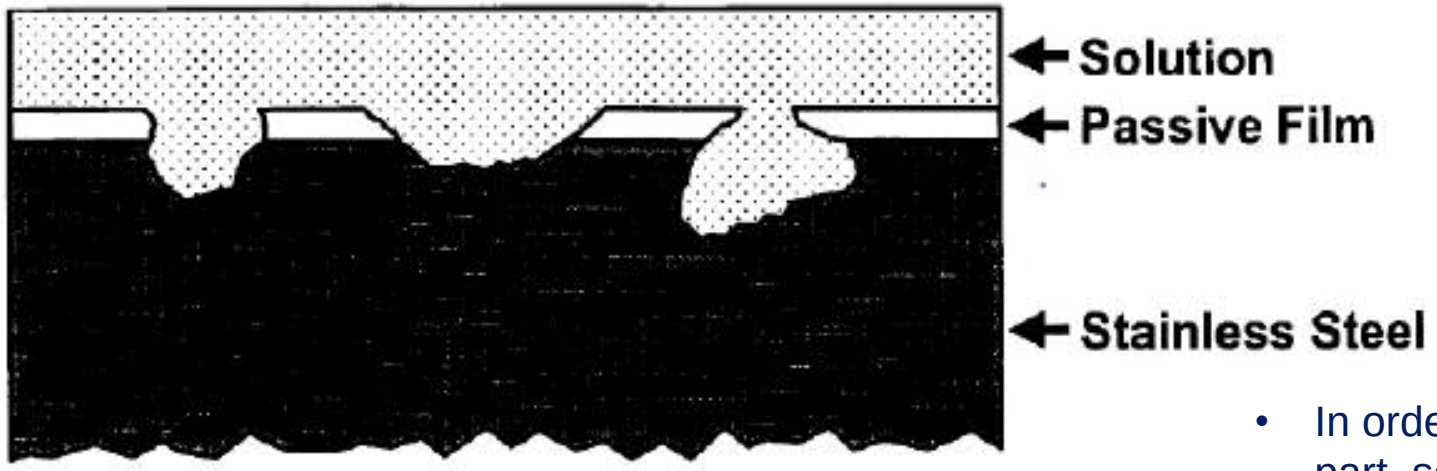
Martensitic
- Cr is the major alloying element
- Cr can be decreased by increasing C content
- Brittle

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

TASNİF DIŞI

STAINLESS STEEL-CORROSION RESISTANCE

- The unique corrosion resistance of stainless steels is attributed to the existence of a thin, adherent, 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.
- 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.



Commonly used alloys in aeroengines

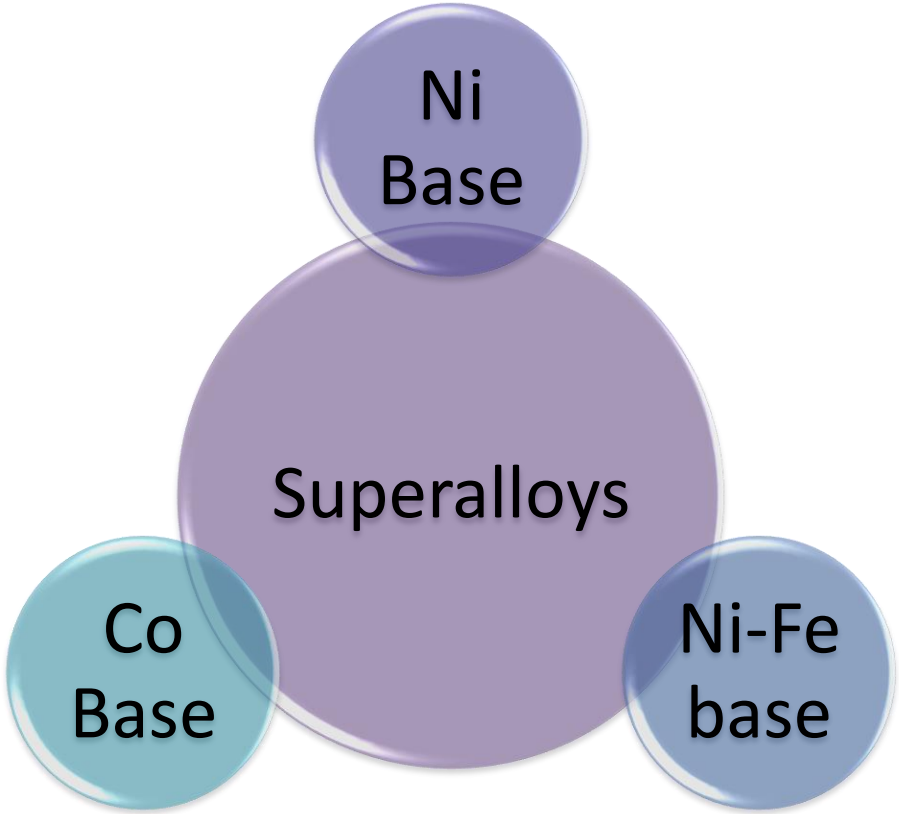
- AISI 304
- AISI 321
- AISI 316
- 17-4PH
- 13-8 PH

- In order to choose which stainless steel to be used for the part, selection must be based on the factors such as chemical environment, pH, temperature, equipment design, fabrication methods, surface finish, contamination, and maintenance procedures

TASNİF DIŞI

SUPERALLOYS

Why are they called **superalloys**?



TASNİF DIŞI

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

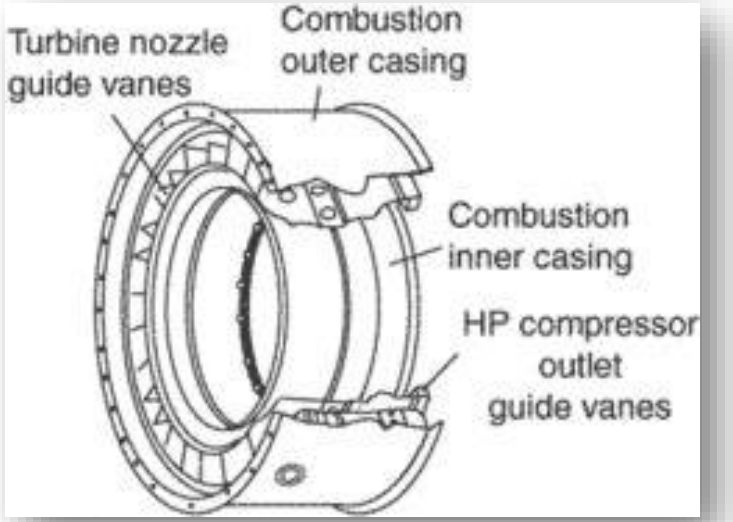
When significant resistance to loading under static, fatigue and creep conditions is required, the nickel-base superalloys have emerged as the materials of choice for high temperature applications. This is particularly true when operating temperatures are beyond about 800 ˚C.

TASNİF DIŞI

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.

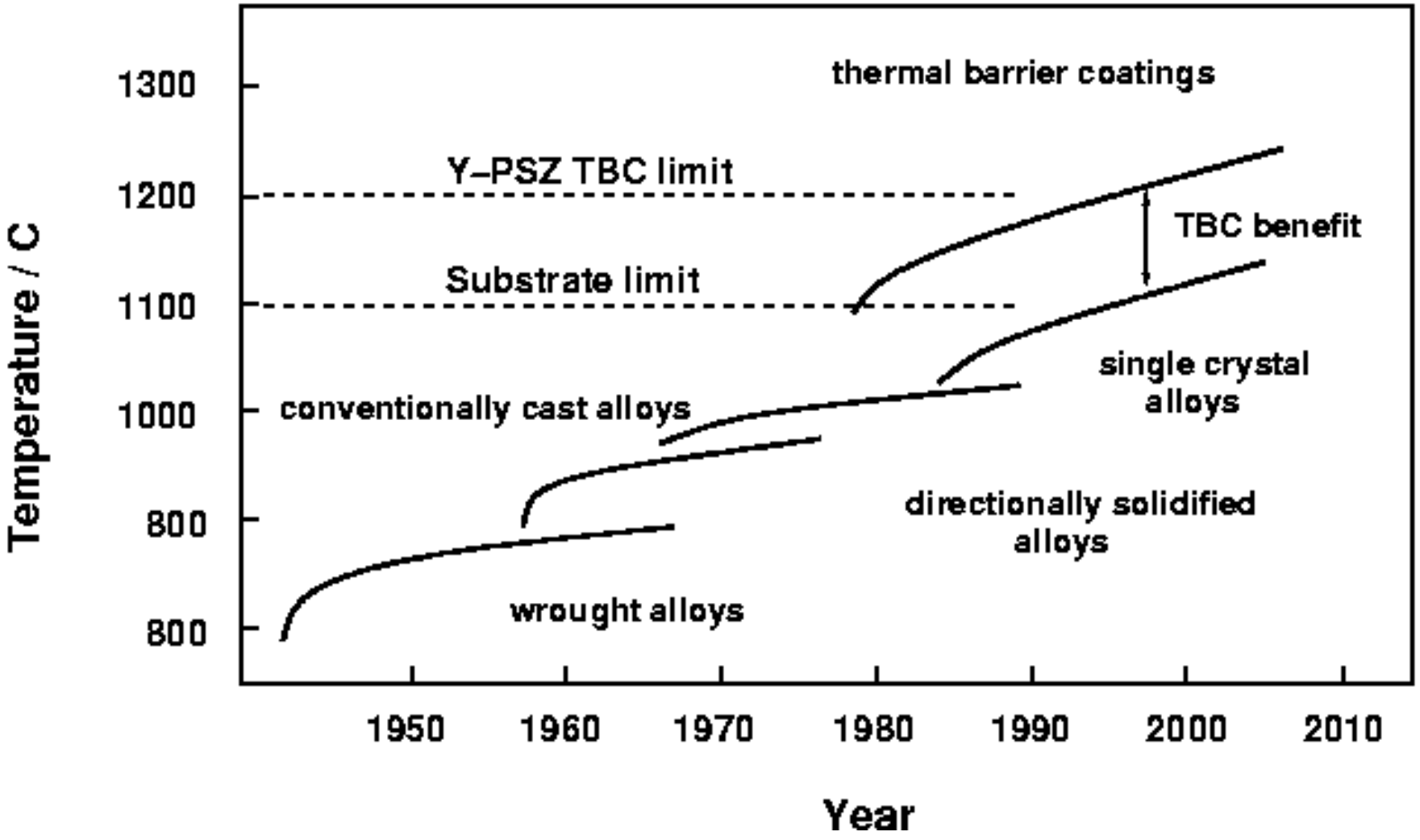


Typical trent engine HP turbine material. Rolls Royce

TASNİF DIŞI

SUPERALLOYS

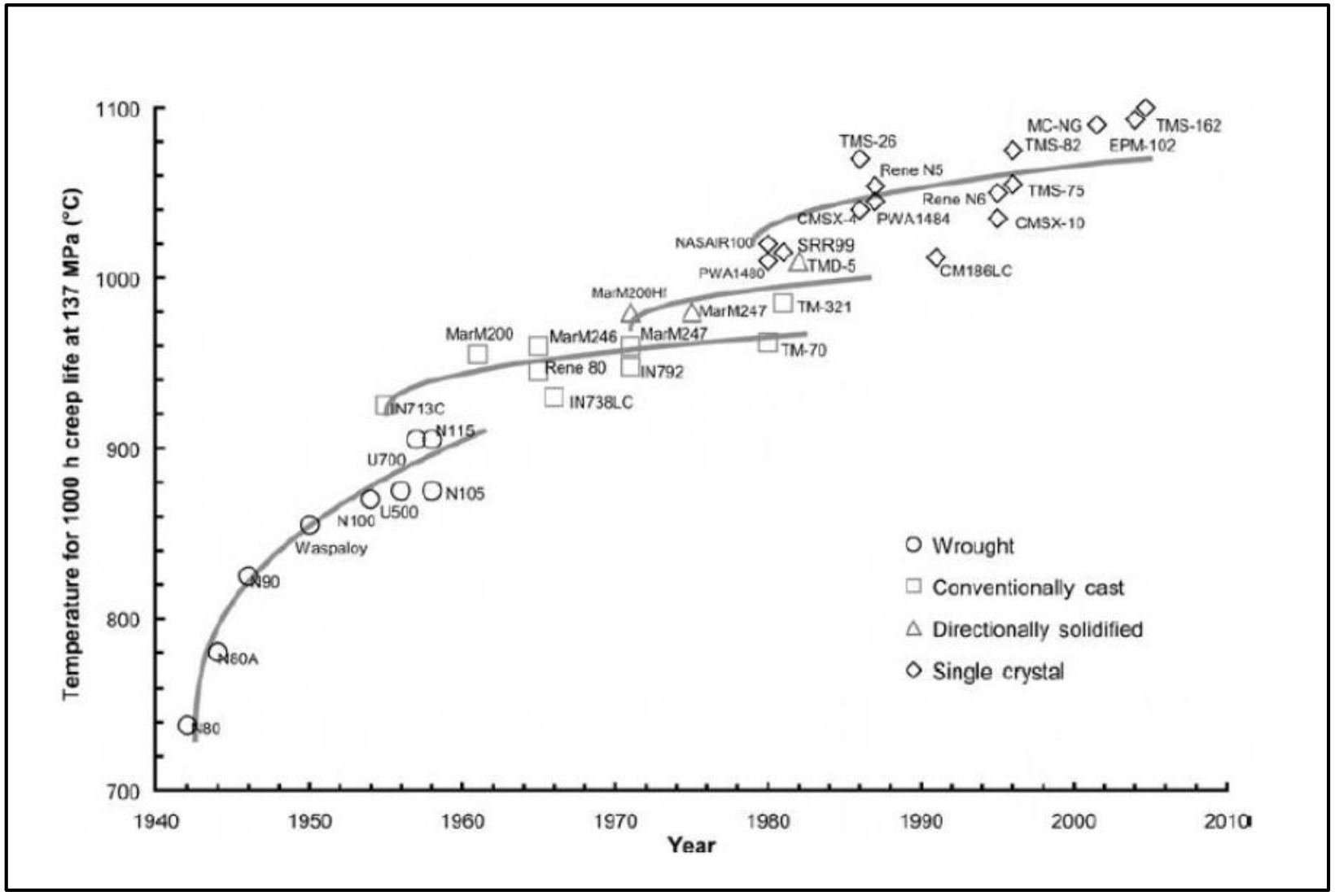
Increase in **operational temperature** of turbine components over the years



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

TASNİF DIŞI

SUPERALLOYS

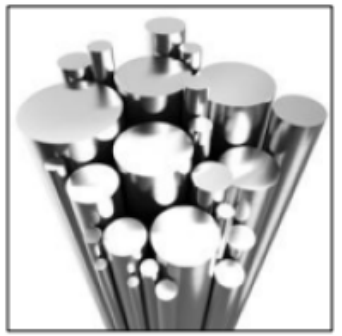


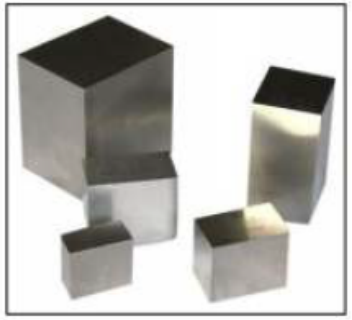
Creep life change of superalloys over the years

TASNİF DIŞI

SUPERALLOYS

Fe-Ni based Super alloys	18-55 %Fe, 10-44%Ni	
	Bar, plate, sheet, forging	
	Example: Inco 718, A286	

Ni based super alloys	50-75 %Ni	
	Bar, plate, sheet, forging, cast	
	Example: Inco 625, Hastelloy X, SX-4	

Co based Super alloys	40-70 % Co	
	Bar, plate, sheet, forging, cast	
	Example: Haynes 25, Haynes 188	

TASNİF DIŞI

NICKEL BASED SUPERALLOYS

Nickel-based superalloys typically constitute 40–50% of the total weight of an aircraft engine and are used most extensively in the combustor and turbine sections of the engine where elevated temperatures are maintained during operation.

Although face-centered cubic (FCC) nickel is the major superalloy constituent, many alloys contain up to 40 wt % of a combination of five to ten other elements

Alloy	Cr	Co	Mo	W	Ta	Re	Nb	Al	Ti	Hf	C	B	Y	Zr	Other
Conventionally Cast Alloys															
Mar-M246	8.3	10.0	0.7	10.0	3.0	—	—	5.5	1.0	1.50	0.14	0.02	—	0.05	—
Rene′ 80	14.0	9.5	4.0	4.0	—	—	—	3.0	5.0	—	0.17	0.02	—	0.03	—
IN-713LC	12.0	—	4.5	—	—	—	2.0	5.9	0.6	—	0.05	0.01	—	0.10	—
C1023	15.5	10.0	8.5	—	—	—	—	4.2	3.6	—	0.16	0.01	—	—	—
Directionally Solidified Alloys															
IN792	12.6	9.0	1.9	4.3	4.3	—	—	3.4	4.0	1.00	0.09	0.02	—	0.06	—
GTD111	14.0	9.5	1.5	3.8	2.8	—	—	3.0	4.9	—	0.10	0.01	—	—	—
First-Generation Single-Crystal Alloys															
PWA 1480	10.0	5.0	—	4.0	12.0	—	—	5.0	1.5	—	—	—	—	—	—
Rene′ N4	9.8	7.5	1.5	6.0	4.8	—	0.5	4.2	3.5	0.15	0.05	0.00	—	—	—
CMSX-3	8.0	5.0	0.6	8.0	6.0	—	—	5.6	1.0	0.10	—	—	—	—	—
Second-Generation Single-Crystal Alloys															
PWA 1484	5.0	10.0	2.0	6.0	9.0	3.0	—	5.6	—	0.10	—	—	—	—	—
Rene′ N5	7.0	7.5	1.5	5.0	6.5	3.0	—	6.2	—	0.15	0.05	0.00	0.01	—	—
CMSX-4	6.5	9.0	0.6	6.0	6.5	3.0	—	5.6	1.0	0.10	—	—	—	—	—
Third-Generation Single-Crystal Alloys															
Rene′ N6	4.2	12.5	1.4	6.0	7.2	5.4	—	5.8	—	0.15	0.05	0.00	0.01	—	—
CMSX-10	2.0	3.0	0.4	5.0	8.0	6.0	0.1	5.7	0.2	0.03	—	—	—	—	—
Wrought Superalloys															
IN 718	19.0	—	3.0	—	—	—	5.1	0.5	0.9	—	—	0.02	—	—	18.5Fe
Rene′ 41	19.0	11.0	10.0	—	—	—	—	1.5	3.1	—	0.09	0.005	—	—	—
Nimonic 80A	19.5	—	—	—	—	—	—	1.4	2.4	—	0.06	0.003	—	0.06	—
Waspaloy	19.5	13.5	4.3	—	—	—	—	1.3	3.0	—	0.08	0.006	—	—	—
Udimet 720	17.9	14.7	3.0	1.3	—	—	—	2.5	5.0	—	0.03	0.03	—	0.03	—
Powder-Processed Superalloys															
Rene′ 95	13.0	8.0	3.5	3.5	—	—	3.5	3.5	2.5	—	0.065	0.013	—	0.05	—
Rene′ 88 DT	16.0	13.0	4.0	4.0	—	—	0.7	2.1	3.7	—	0.03	0.015	—	—	—
N18	11.2	15.6	6.5	—	—	—	—	4.4	4.4	0.5	0.02	0.015	—	0.03	—
IN100	12.4	18.4	3.2	—	—	—	—	4.9	4.3	—	0.07	0.02		0.07	

Some common nickel based superalloys

For turbine section materials, nickel based superalloys are commonly used

TASNİF DIŞI

COBALT BASED SUPERALLOYS

- 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
- Cobalt crystallizes in the hcp structure below 417 °C. At higher temperatures, it transforms to fcc. To avoid this transformation during service, virtually all cobalt-base alloys are alloyed with nickel in order to stabilize the fcc structure between room temperature and the melting point.
- Cast alloys are typied by X-40 and wrought alloys by L605
- Due to high Cr content, oxidation resistance at high temperatures are better. Display superior hot corrosion resistance at high temperatures
- exhibit better weldability and thermal-fatigue resistance than do nickel-base alloys.
- However, unlike nickel-base alloys, which have a high tolerance for alloying elements in solid solution, cobalt-base alloys are more likely to precipitate undesirable plate-like σ, and TCP phases.

Cobalt based superalloys are selected generally parts working under slightly lower stress and high temperature. Requiring high corrosion resistance. Such as combustor chamber parts

TASNİF DIŞI

IRON-NICKEL BASED SUPERALLOYS

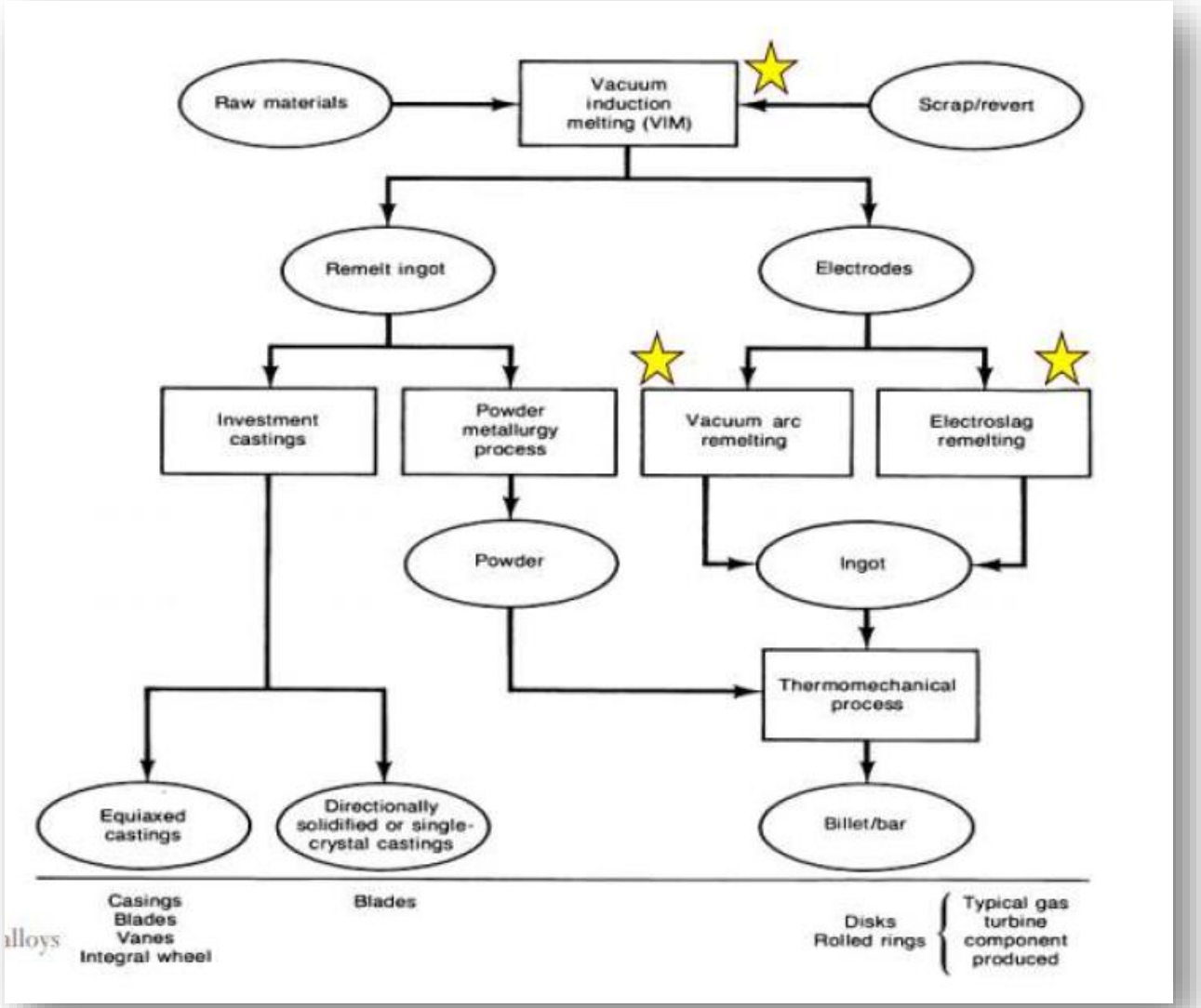
- Fe is added to replace some Ni as it has lower cost
- evolved from austenitic stainless steels and are based on the principle of combining a closed-packed fcc matrix with (in most cases) both solid-solution hardening and precipitate-forming elements.
- Ni-Fe superalloys contain 25-45 %Ni and 15-60 %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
- high temperature as well as room temperature strength
- Good resistance to creep, oxidation, corrosion and wear
- Inconel 700, 718, 901

- Inconel 718 is one of the strongest (at low temperatures) and most widely used of all superalloys, but it rapidly loses strength in the range of 650 to 815 °C. This is probably due to the high lattice misfit associated with the precipitation of γ" in the austenitic matrix.

Whenever temperature and stress requirements are satisfied, Inconel 718 alloy can be used in the engine parts. This alloy can be the most common used superalloy

TASNİF DIŞI

SUPERALLOYS-PROCESSING

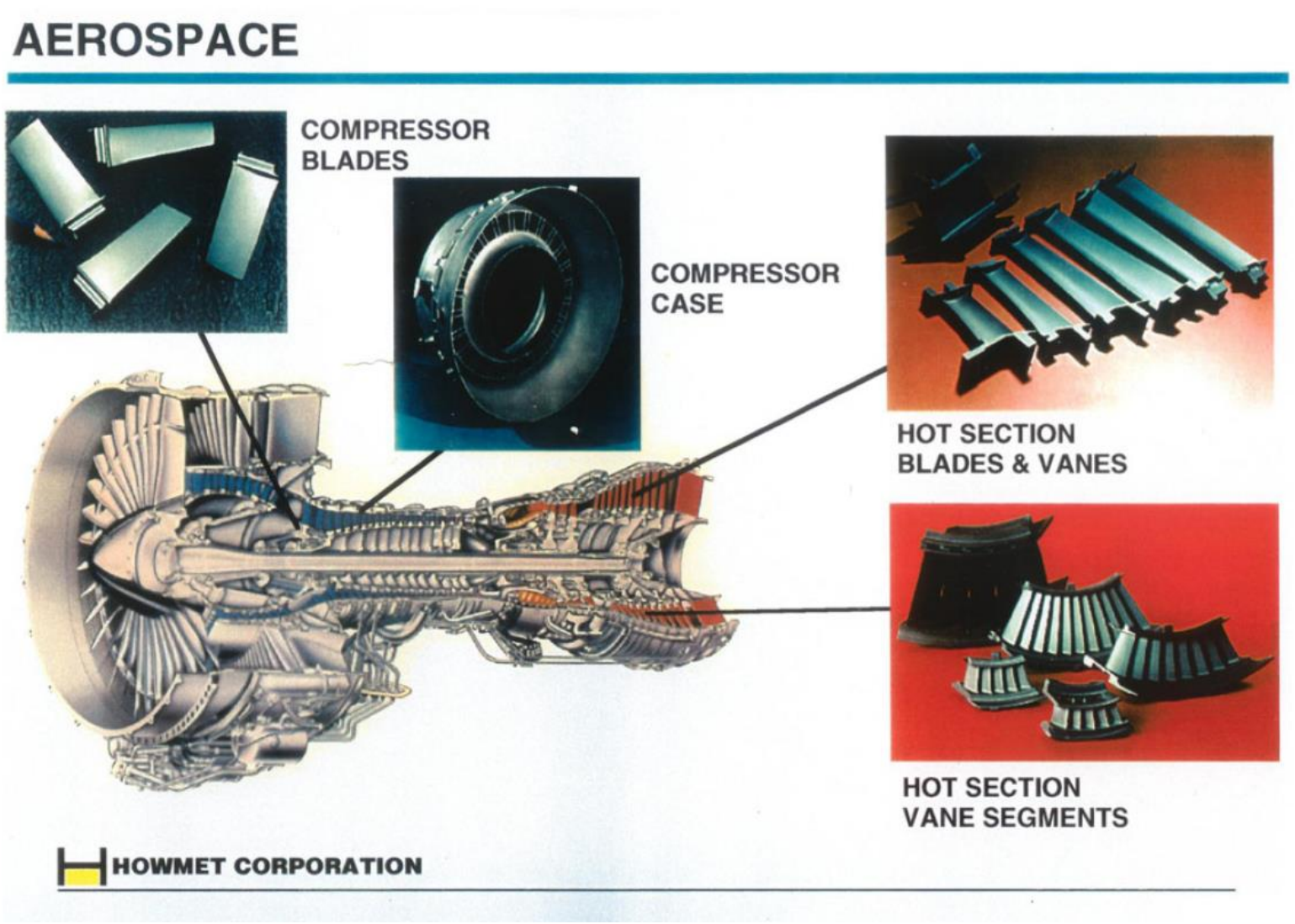


Processing begins with the fabrication of large ingots that are subsequently used for one of three major processing routes:

- 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.

TASNİF DIŞI

SUPERALLOYS-CASTING



Turbine blades vanes are generally produced by casting

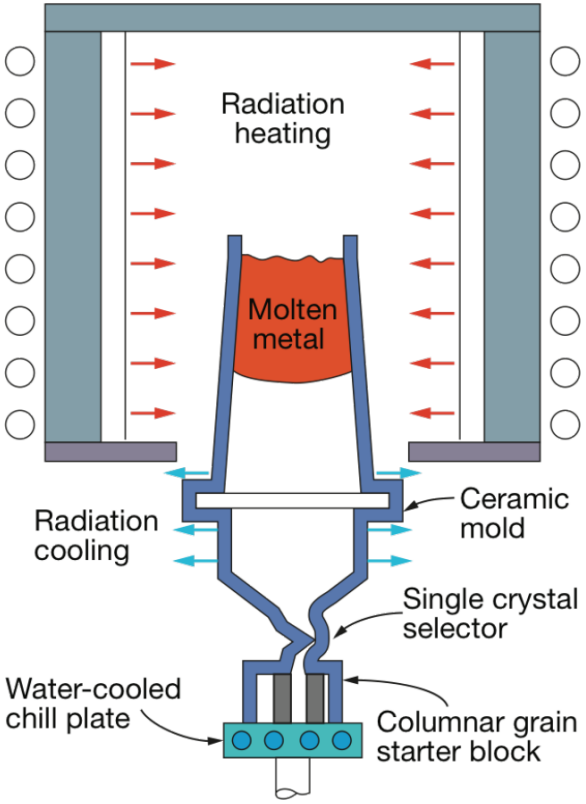
TASNİF DIŞI

SUPERALLOYS-INVESTMENT CASTING

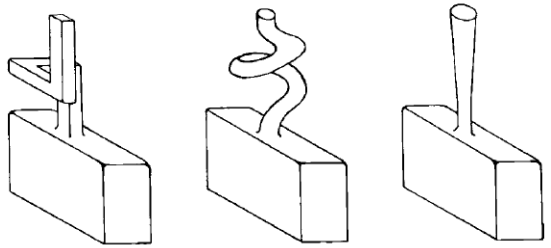
Schematic showing the investment casting process of the superalloys. Equiaxed, directionally solidified (DS) or single crystal (SX) alloys may be casted following this method.

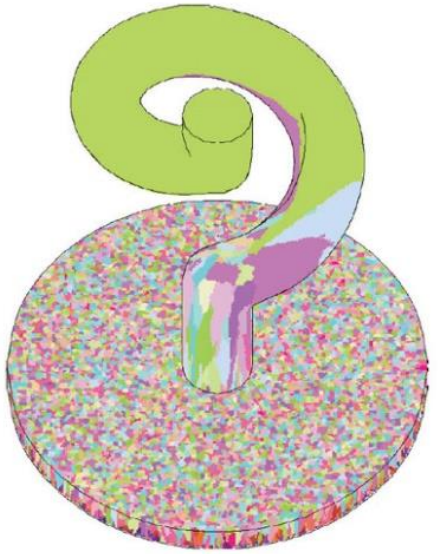
TASNİF DIŞI

DIRECTIONALLY SOLIDIFIED ALLOYS-SINGLE CRYSTAL ALLOYS



For DS and SX materials cooling of the part shall ve performed slowly and controlly. Furthermore, To achieve SX materials Pig tail geometries shall be used.



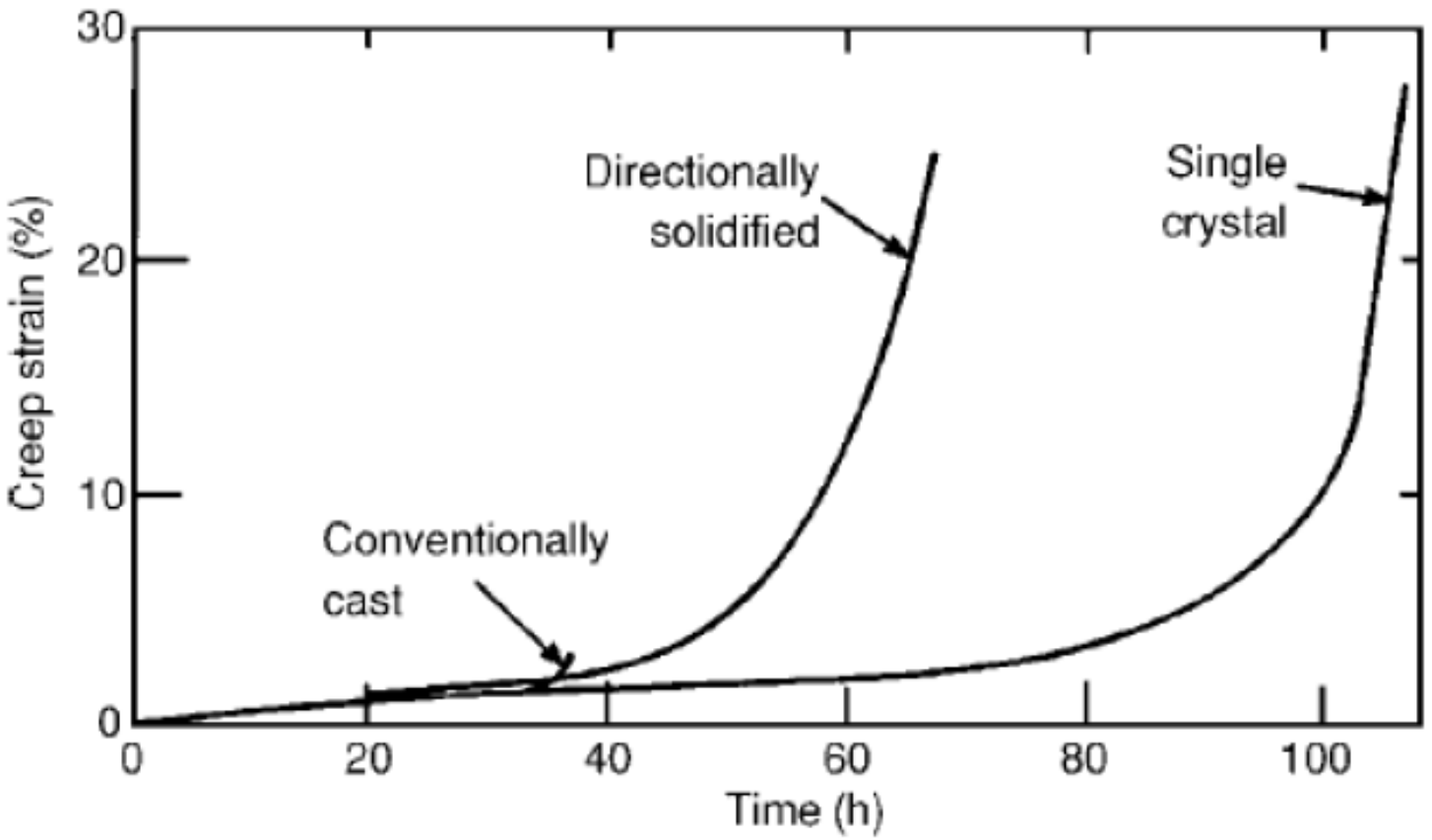


SX materials based on different generations

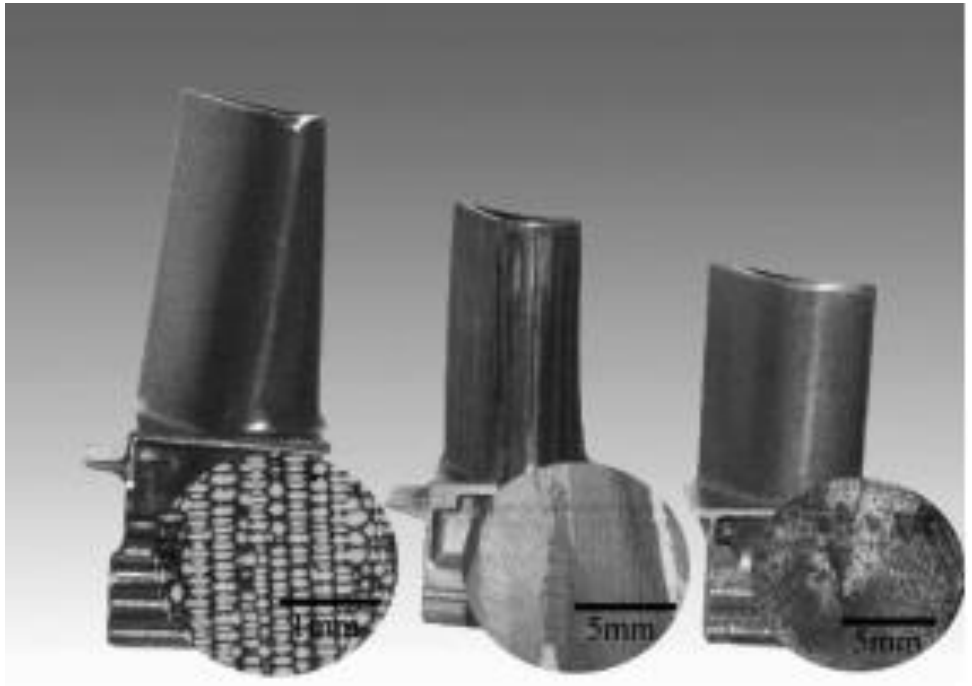
	Cr	Co	Mo	W	Ta	V	Nb	Al	Ti	Hf	Re
1st Generation											
PWA1480	10	5	0	4	12			5	1.5	0	
Rene N4	9	8	2	6	4		0.5	3.7	4.2	0	
SRR99	8	5	0	10	3			5.5	2.2	0	
RR2000	10	15	3	0	0	1		5.5	4	0	
AM1	8	6	2	6	9			5.2	1.2	0	
AM3	8	6	2	5	4			6	2	0	
CMSX2	8	5	0.6	8	6			5.6	1	0	
CMSX3	8	5	0.6	8	6			5.6	1	0.1	
CMSX6	10	5	3	0	2			4.8	4.7	0.1	
AF56	12	8	2	4	5			3.4	4.2	0	
										0	
2nd Generation											
CMSX4	7	9	0.6	6	7			5.6	1	0.1	3
PWA1484	5	10	2	6	9			5.6	0	0.1	3
SC180	5	10	2	5	9			5.2	1	0.1	3
MC2	8	5	2	8	6			5	1.5	0	0
Rene N5	7	8	2	5	7			6.2	0	0.2	3
										0	
3rd Generation											
CMSX10	2	3	0.4	5	8			5.7	0.2	0.03	6
Rene N6	4.2	12.5	1.4	6	7.2		0.1	5.75	0	0.15	5.4
TMS75	3	12	2	6	6			6	0	0.1	5
TMS113	2.89	11.93	1.99	5.96	5.96			6.56	0	0.1	5.96
	Cr	Co	Mo	W	Ta	V	Nb	Al	Ti	Hf	Re

TASNİF DIŞI

CONVENTINAL -DIRECTIONALLY SOLIDIFIED-SINGLE CRYSTAL



DS and especially Sx materials are chosed for their creep performans. As seen from the graph, SX materials significantly better than conventionally cast equiaxed alloys in terms of creep and stress rupture



Depending on the stress, temperature and life requirements of the parts, casting method and materials can be selected. SX alloys show better creep properties but tensile properties are not much different than other casting alloys. And also SX alloys are more expensive and difficult to produce, trade off must be done for the best materials selection.

TASNİF DIŞI

WROUGHT PRODUCTS

Standard products

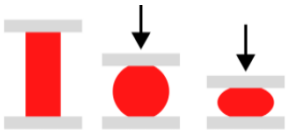
Engine parts can be machined from bar products, sheet products etc depending on the part geometry.

TASNİF DIŞI

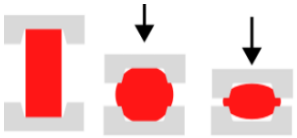
FORGING

Forging Types

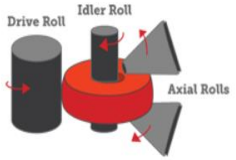
Open Die Forging



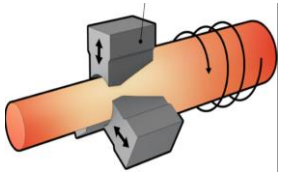
Close Die Forging



Ring Rolling



Radial Forging



Equipments

Presses

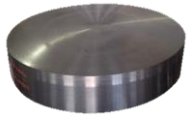
Hammer

Ring Machine

Radial Forging Machine

Semi Products

Pancake (Blank) Forgings



Near Net Shape Forgings

Seamless Rings

Bars & Billets

Turbine Disks

Impellers & Blades

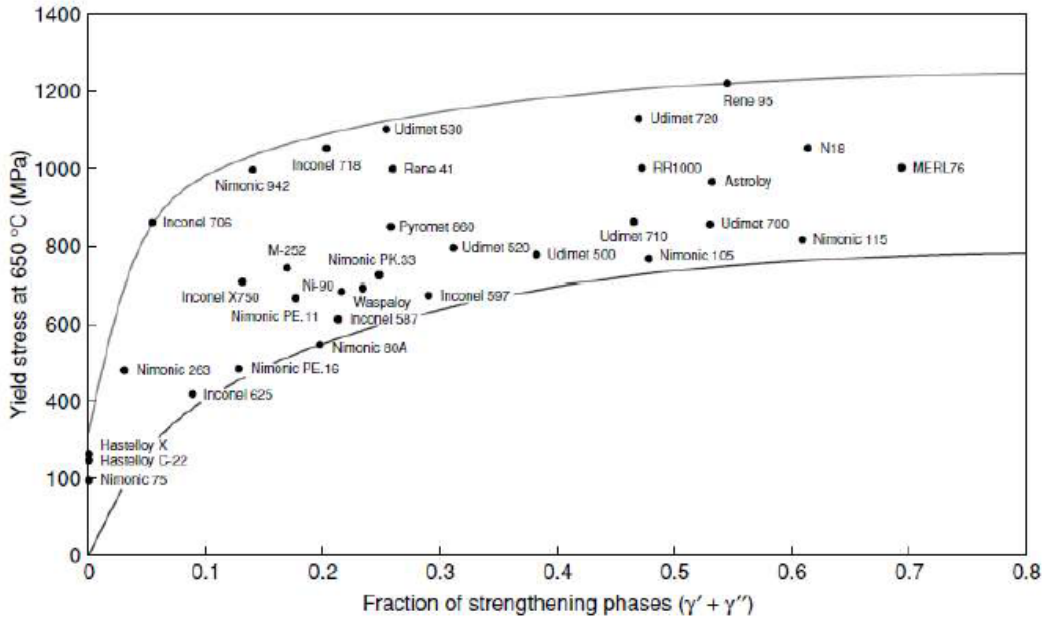
Shroud & Casings

General forging method types , equipments.. Especially, for the critical parts such as discs forged materials are selected

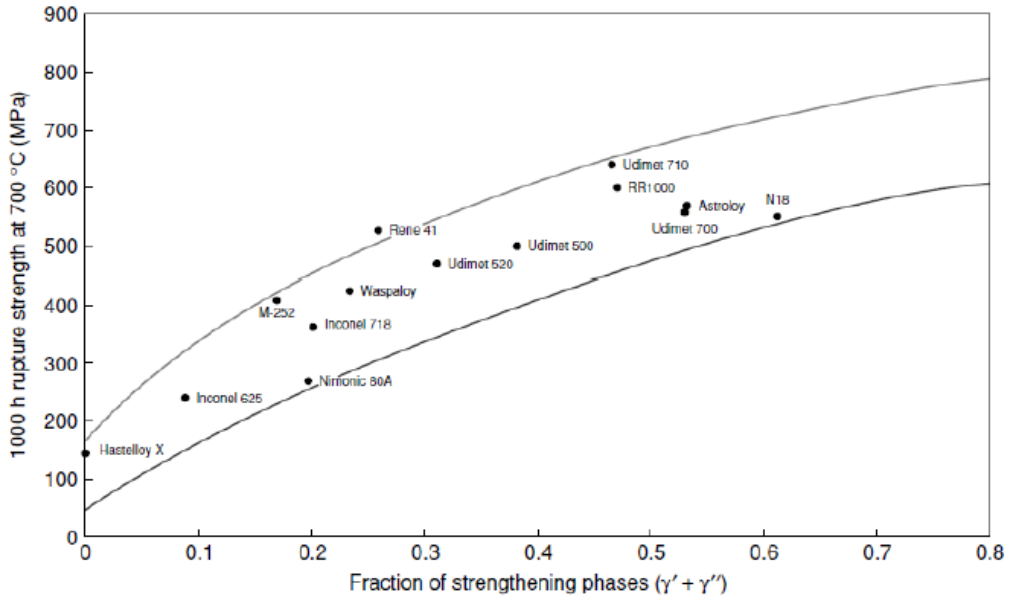
Forging is one of the most commonly used production method for engine materials

TASNİF DIŞI

WROUGHT SUPERALLOYS



Variation of the yield stress at 650C with the total fraction of the gamma prime and gamma double prime strengthening phases



Variation of 1000h creep rupture strength at 700C with the total fraction of the gamma prime and gamma double prime strengthening phases

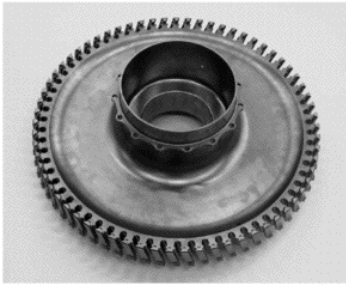
Mechanical properties of some common wrought superalloys are given for comparison.

Note that wrought alloys work at slightly lower temperatures compared to casted alloys. Therefore, for parts line discs, impellers,cases.. Etc wrought alloys are selected

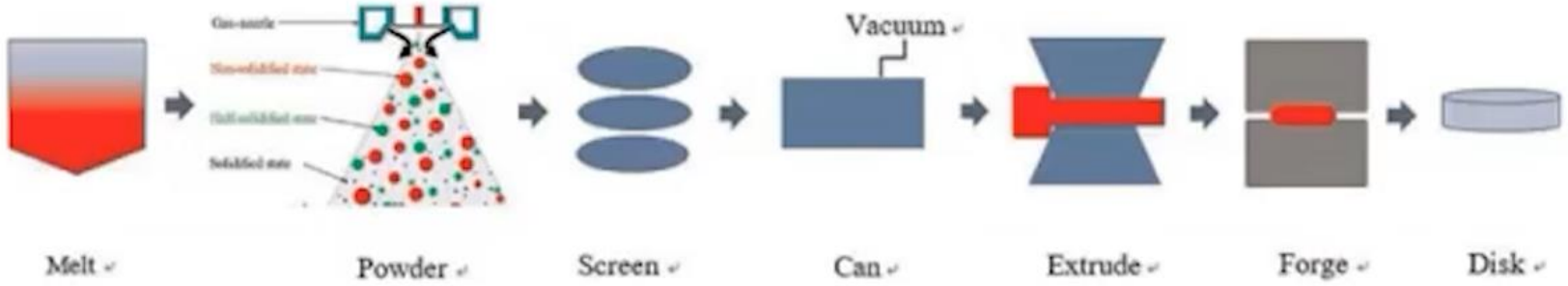
TASNİF DIŞI

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.
- the concentration of inclusions will be lower in the powder metallurgy



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



TASNİF DIŞI

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.

Significant Process: A process or process sequence that if changed could affect design intent; might affect material physical, chemical, electrical, mechanical or metallurgical properties; and 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

TASNİF DIŞI

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

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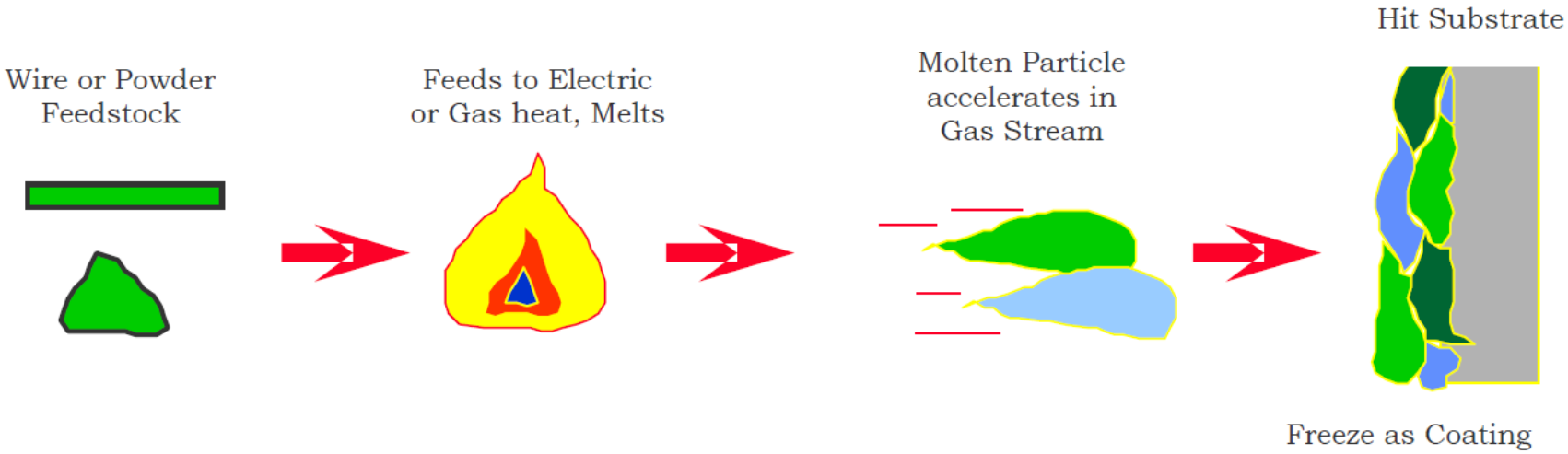
SPECIAL PROCESSES- THERMAL SPRAY COATINGS



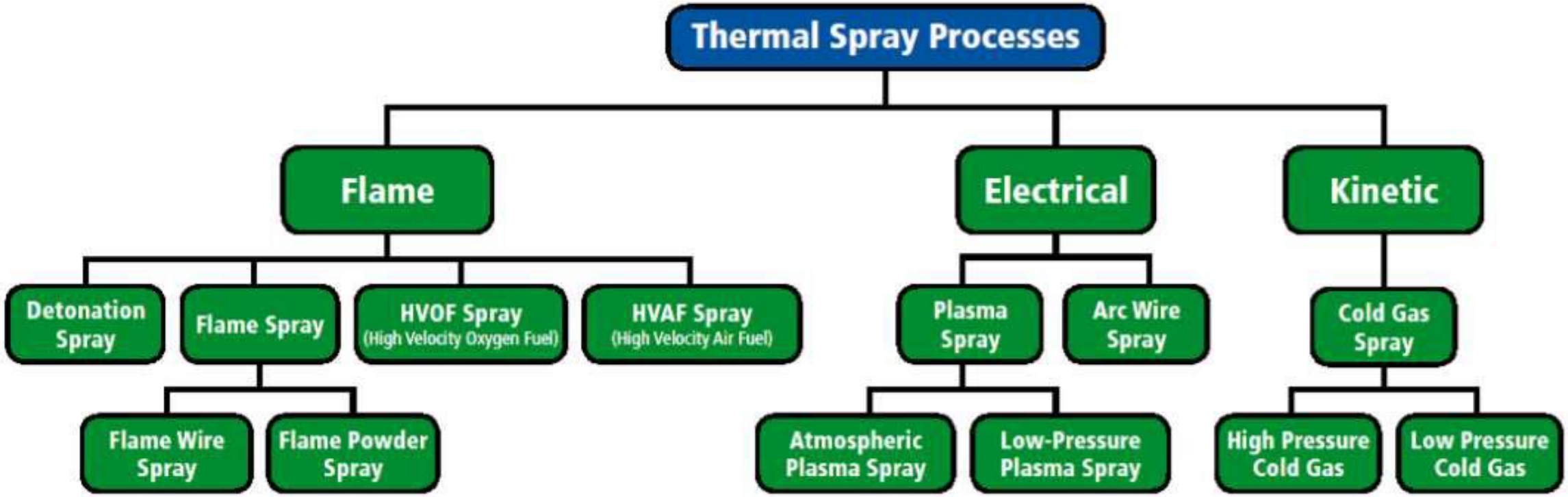
Thermal Spray is a technique by which a material is melted and transported to the substrate, cools to form a coating.

Coating Types used in aerospace industry

- Thermar Barrier Coating
- Anti-wear Coatings
- Abradable Coatings
- Abrasive Coatings

TASNİF DIŞI

SPECIAL PROCESSES- THERMAL SPRAY COATINGS



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 Flame, Electrical and Kinetic.

TASNİF DIŞI

SPECIAL PROCESSES- 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

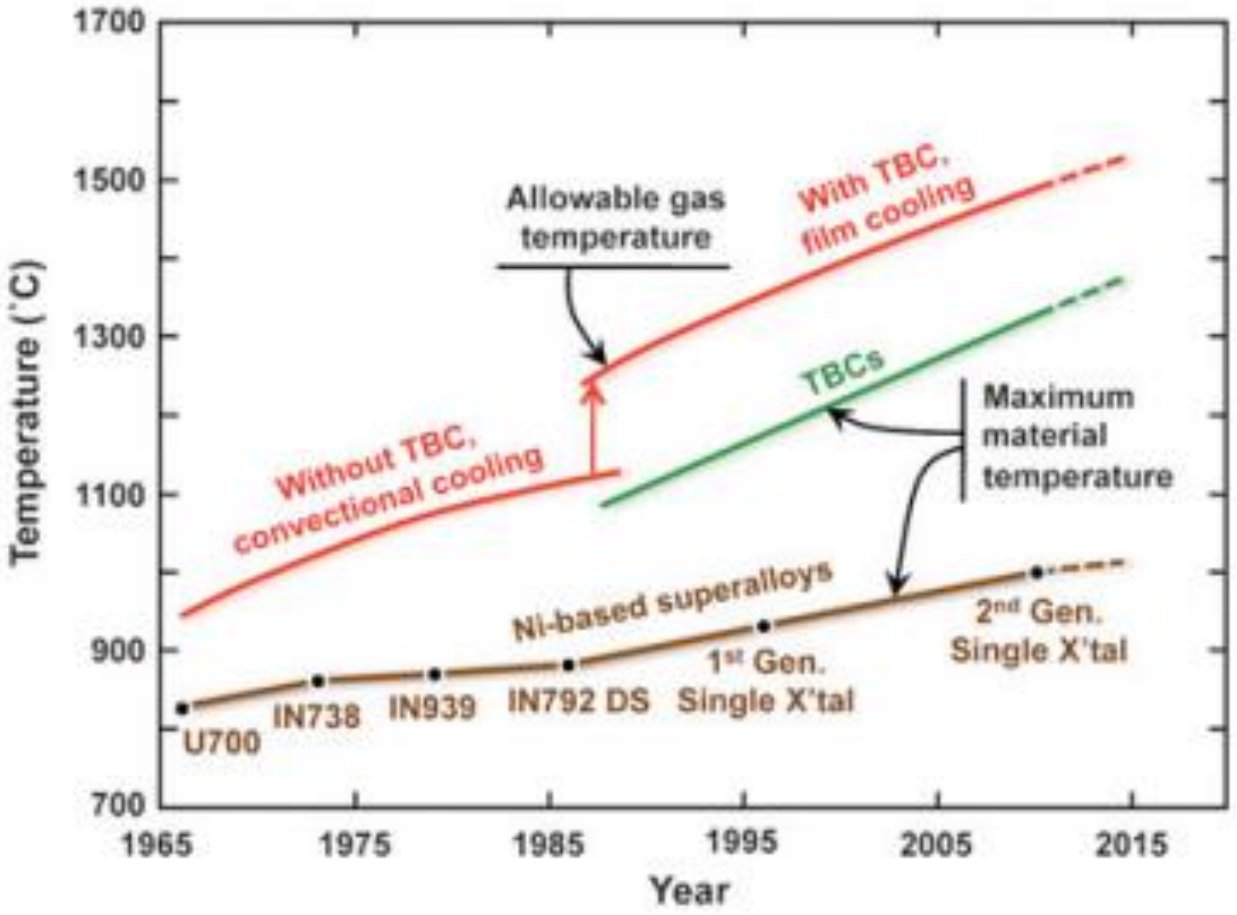
Sealing

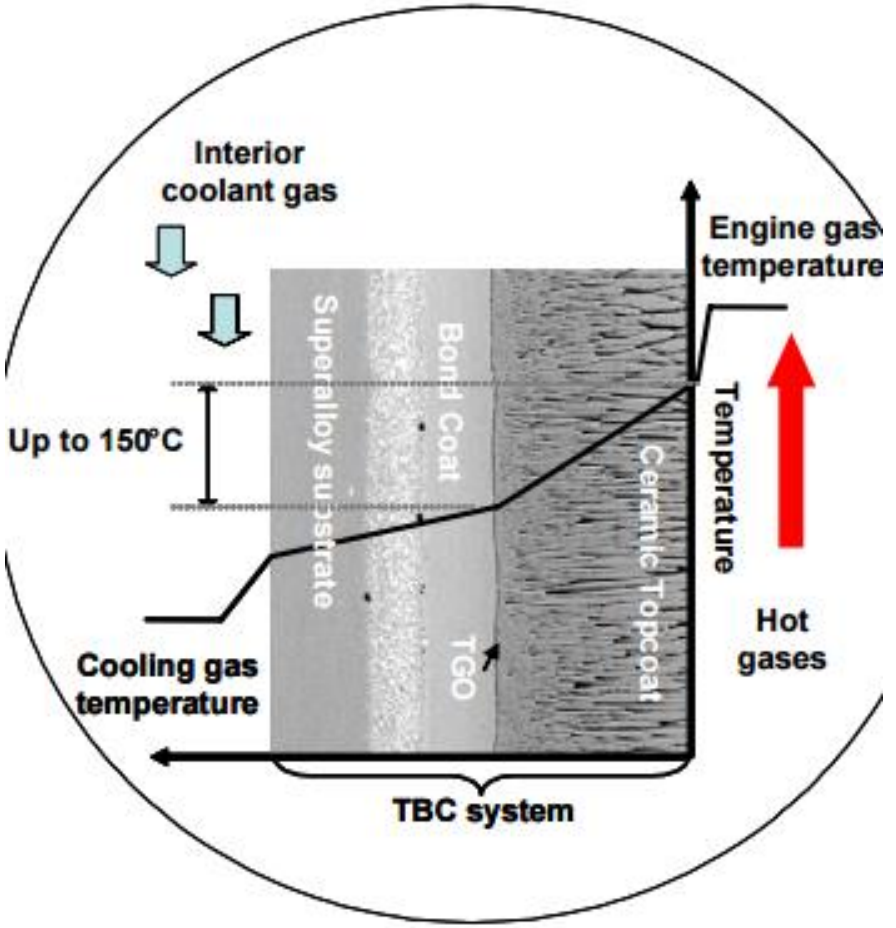
- Restoration Coatings

Build-up restorations

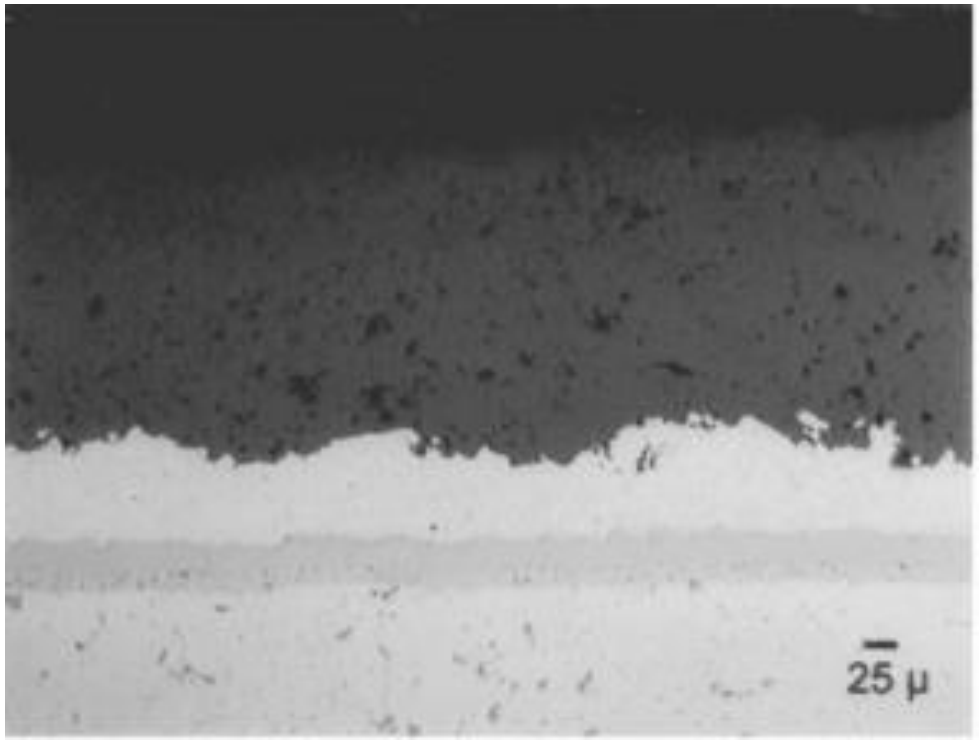
TASNİF DIŞI

THERMAL BARRIER COATINGS

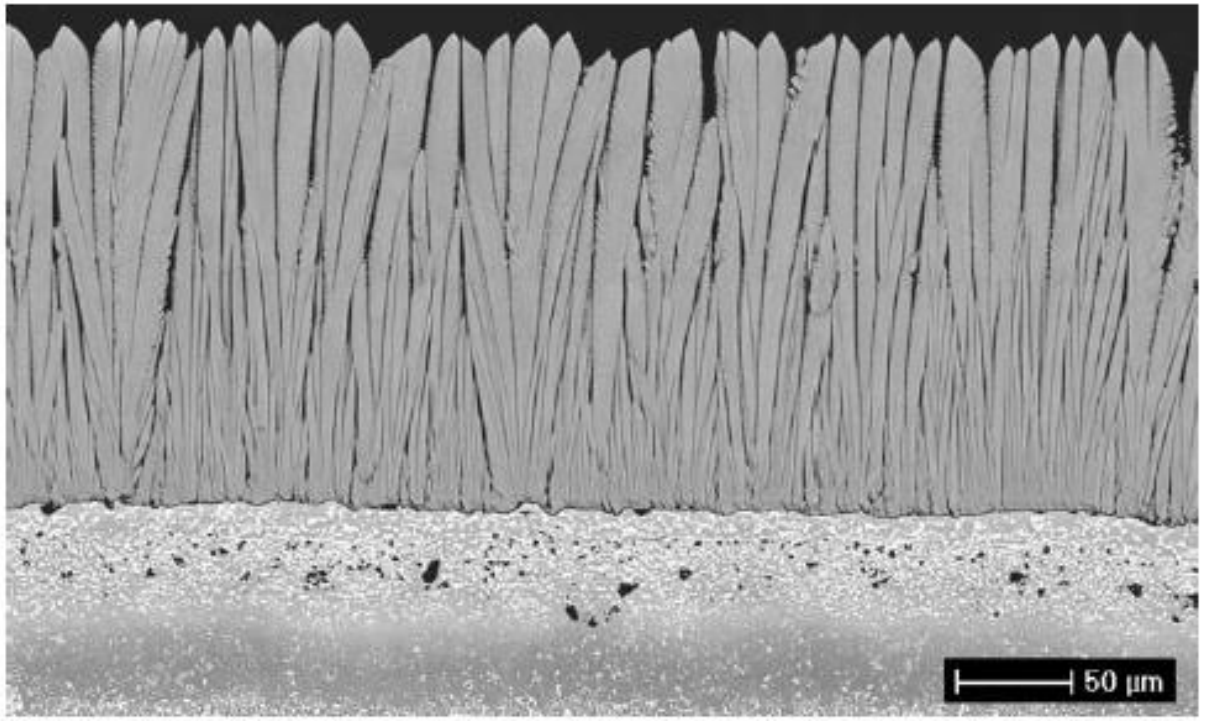




THERMAL BARRIER COATINGS



Air Plasma Spray (APS)



Electron Beam-Physical Vapor Deposition(EB-PVD)

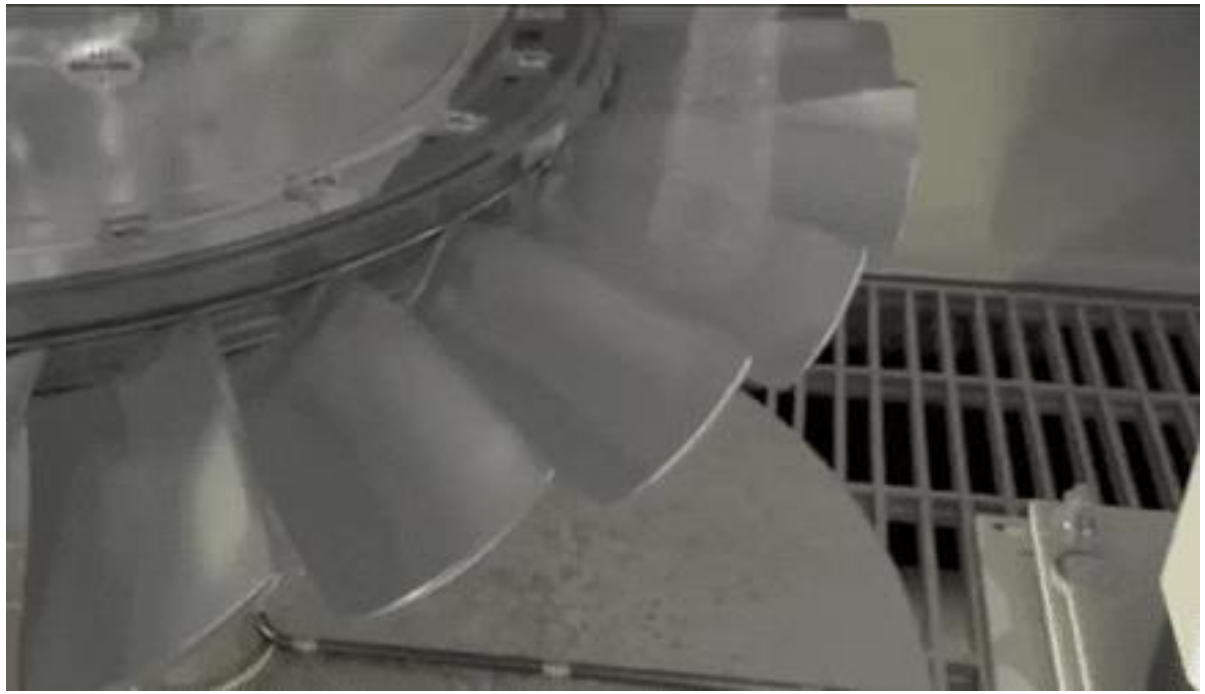
THERMAL BARRIER COATINGS

Yttria-stabilized zirconia and magnesium-stabilized zirconia are the main TBC coatings. Metallographic evaluation is the main test and care not to pullout the ceramic coating must be applied. These coatings are primarily used on combustors and flameholders.

Yttria Stabilized Zirconia

- Yttria stabilized zirconia coatings are used as thermal barrier coating on high temperature regions of engine.
- Coating provides thermal insulation and corrosion resistance to applied components.
- The coatings are 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.

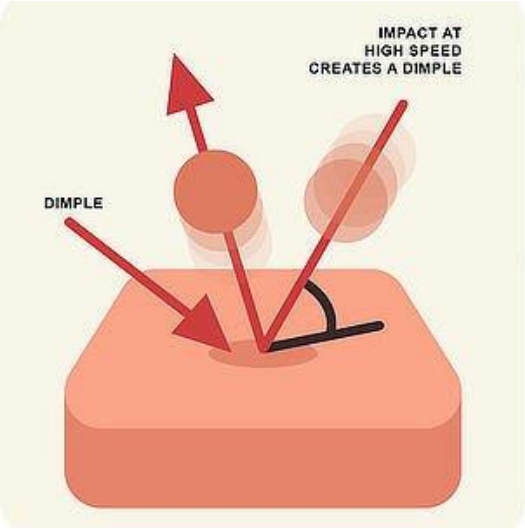
SPECIAL PROCESSES- SHOT PEENING



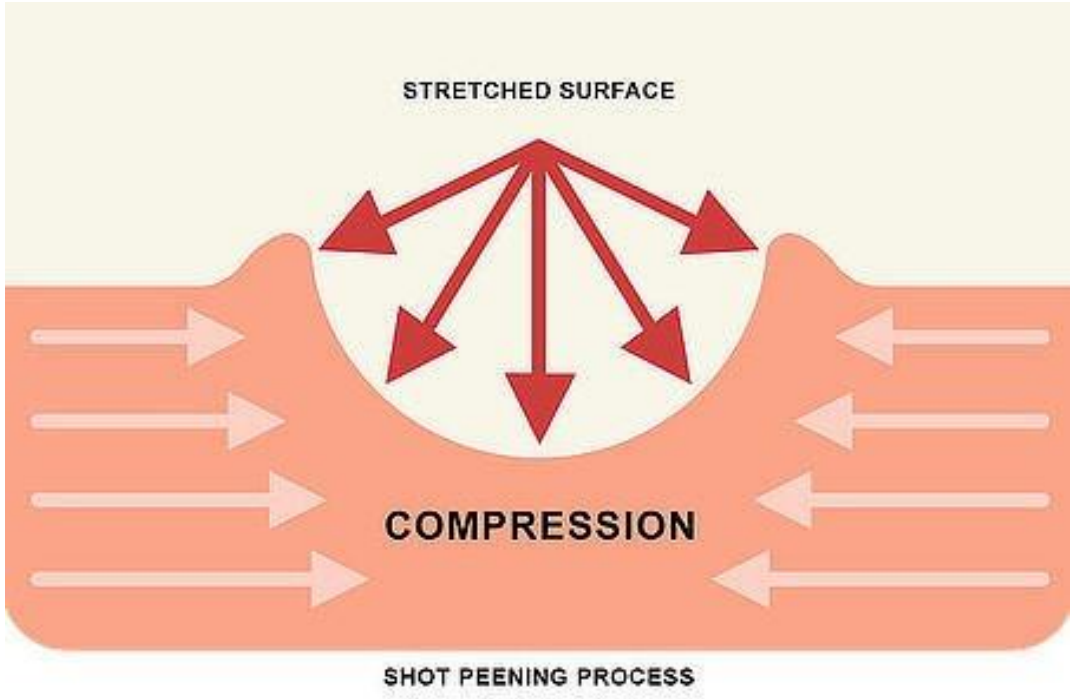
Shot peening is a method of cold working in which compressive stresses are induced in the exposed surface layers of metallic parts by the impingement of a stream of shot, directed at the metal surface at high velocity under controlled conditions.

TASNİF DIŞI

SPECIAL PROCESSES- 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.



TASNİF DIŞI

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

GÜCÜN KAYNAĞI

TEŞEKKÜRLER

TASNİF DIŞI

TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Termal Sistem Tasarım Teknik Rehber

08.12.2022

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TASNİF DIŞI

CONTENT

- Introduction to Heat Transfer in Gas Turbines
- Heat Transfer Interfaces
- Heat Transfer Mechanisms in Gas Turbines
  - Conduction
  - Convection
  - Radiation
- 1D - Resistance Network Approach
- Afterburner Examples
- Heat Transfer Calculations for Afterburner Parts
- Cooling Design
  - Film Cooling
  - Effusion Cooling
- Closing Remarks

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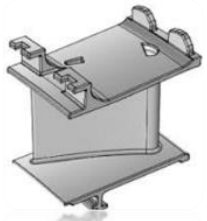
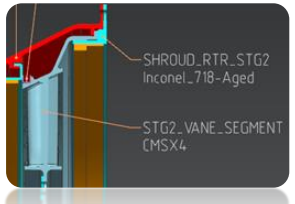
Heat Transfer in Gas Turbines: Thermal Analysis Step

INPUTS

Mechanical Design
- Geometry



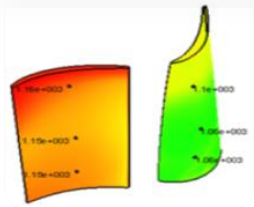
Material
- Thermophysical Properties



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

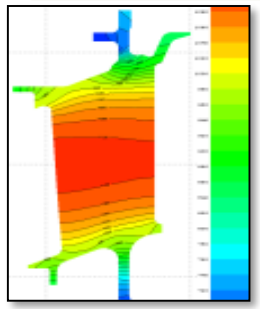
Aerodynamic / Combustion Design
- Gas Temps
- HTC



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.

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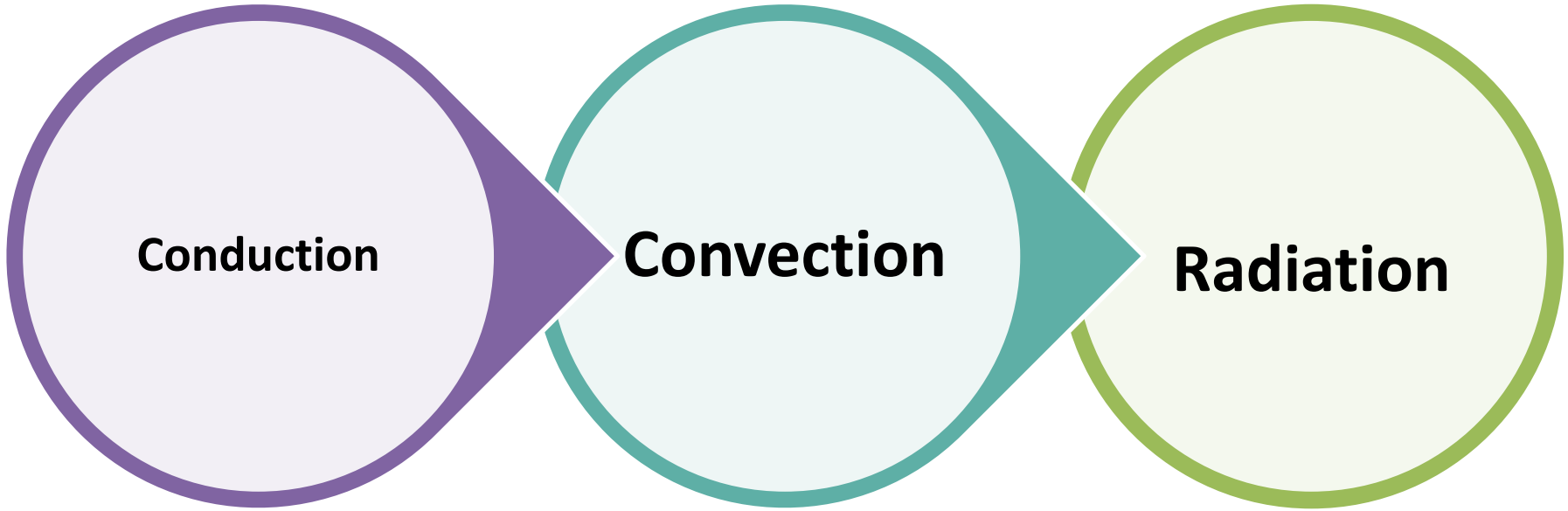
Heat Transfer Mechanisms



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

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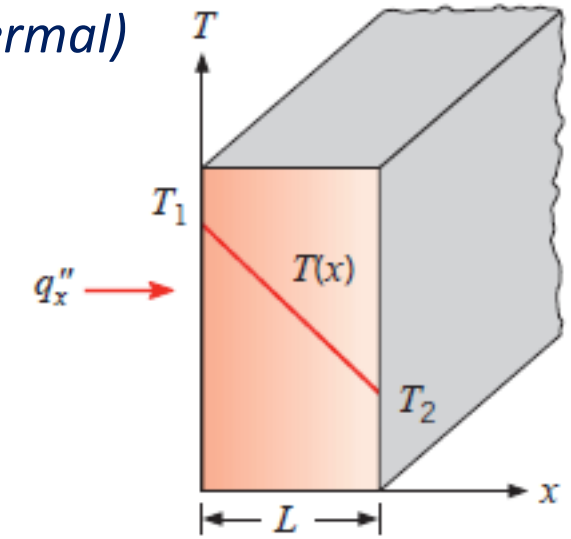
Heat Transfer Mechanisms: Conduction

Conduction

- **Interfence 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)*

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



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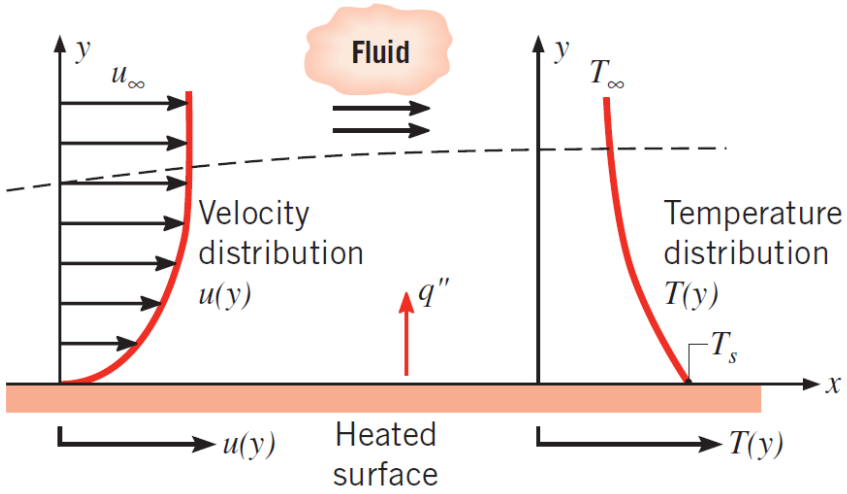
Heat Transfer Mechanisms: Convection

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*

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



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

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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.

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

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

T_{∞} = Free stream fluid temperature

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

Turbulent flow: $r = (Pr)^{1/3}$

Laminar flow: $r = (Pr)^{1/2}$

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Heat Transfer Mechanisms: Radiation

Radiation

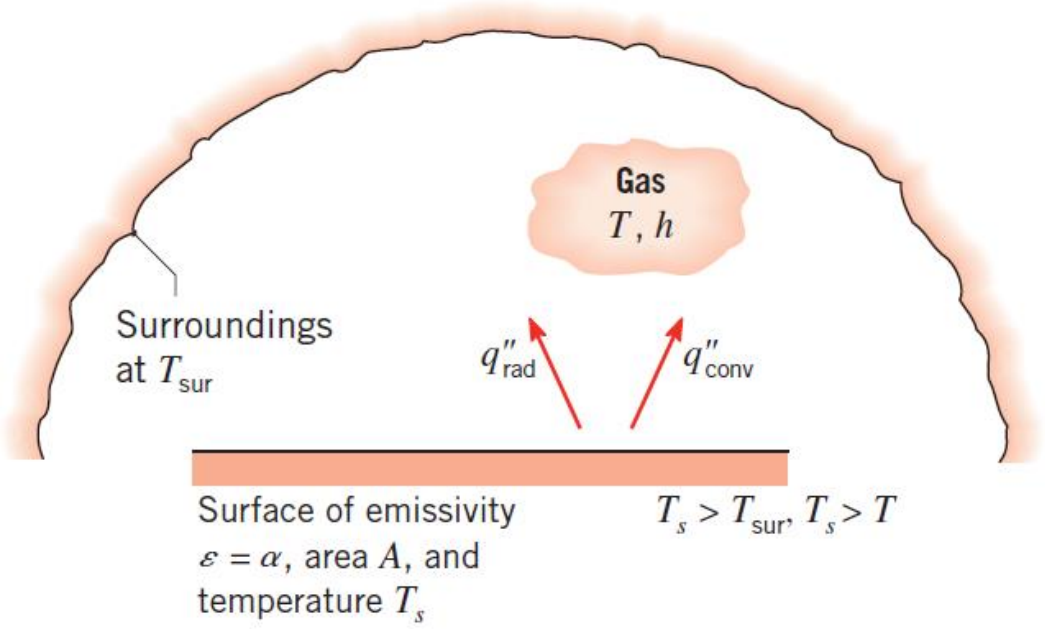
- Cavities (Rotor – Stator)
- Blade Shank

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

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

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

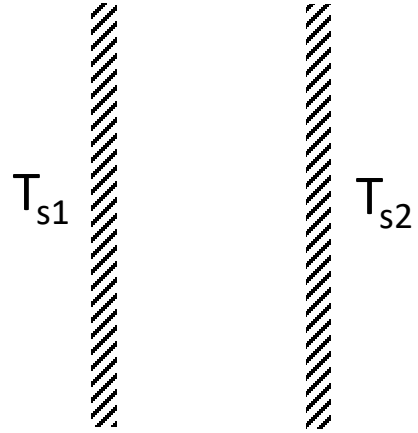
ε=Surface emissivity, $0 \leq \varepsilon \leq 1$



Heat Transfer Mechanisms: Radiation

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

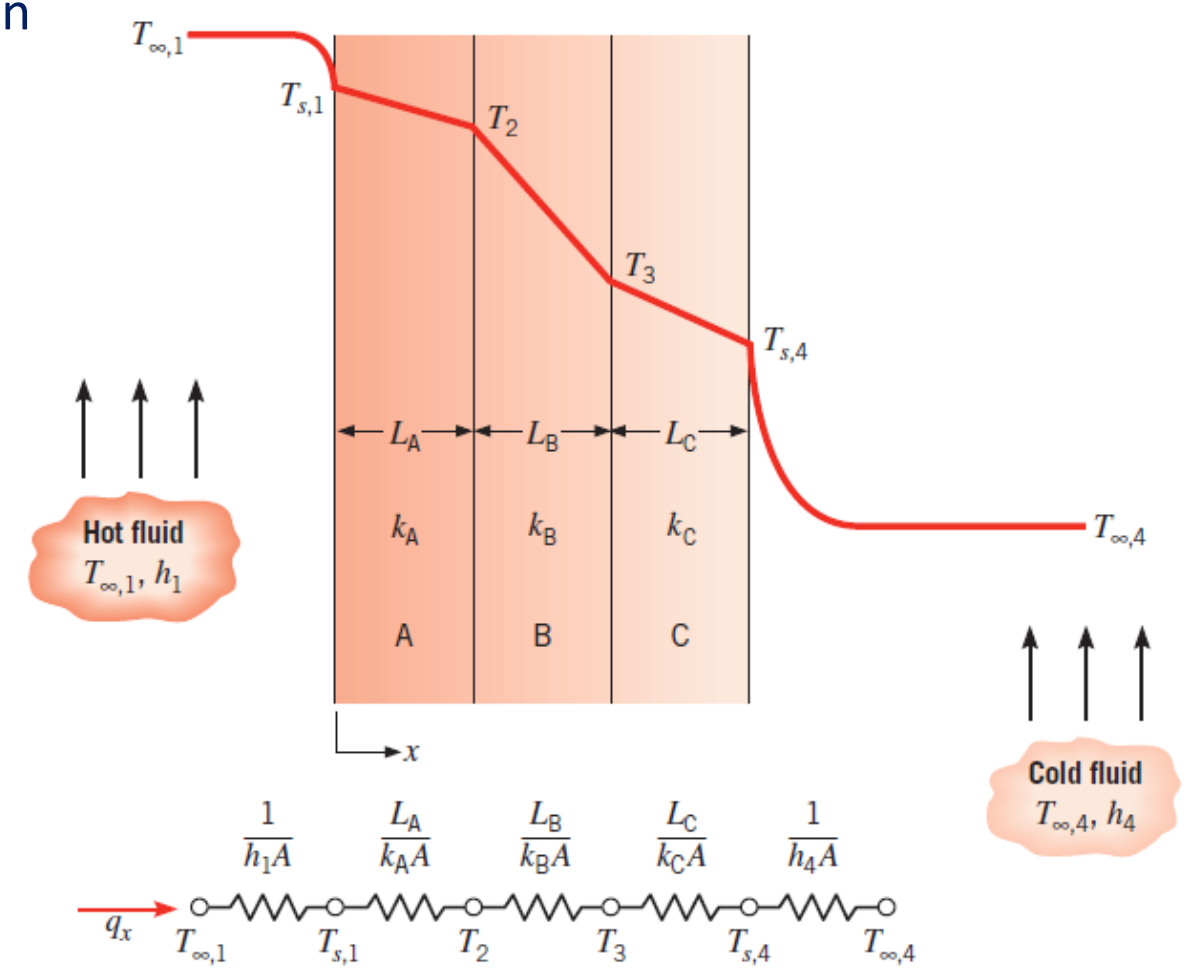
$\dot{Q}_{1-2} \equiv$ Net radiation heat transfer rate from surface 1 to surface 2
$\varepsilon_1 \equiv$ Surface 1 emissivity
$\varepsilon_2 \equiv$ Surface 2 emissivity
$A_1 \equiv$ Heat transfer area of surface 1
$A_2 \equiv$ Heat transfer area of surface 2
$F_{1-2} \equiv$ View factor between surfaces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



Radiation exchange across gap

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.



$$q_x = UA\Delta T$$

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

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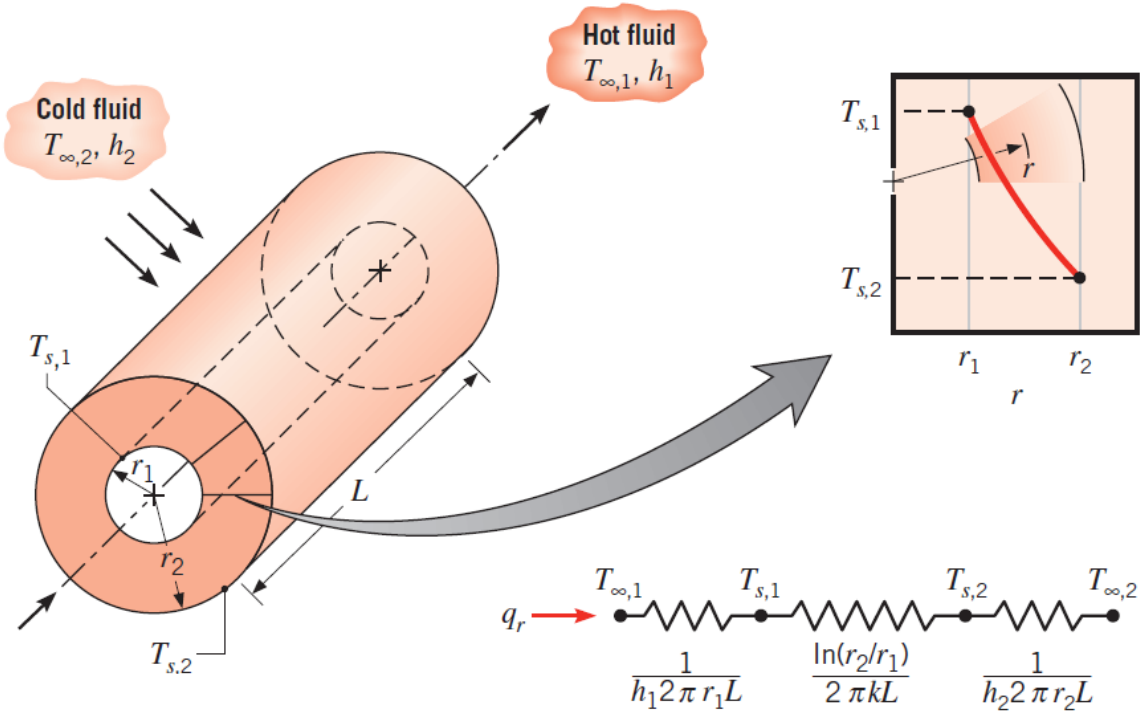
1D Resistance Network Approach: Radial Systems

- 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.



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

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

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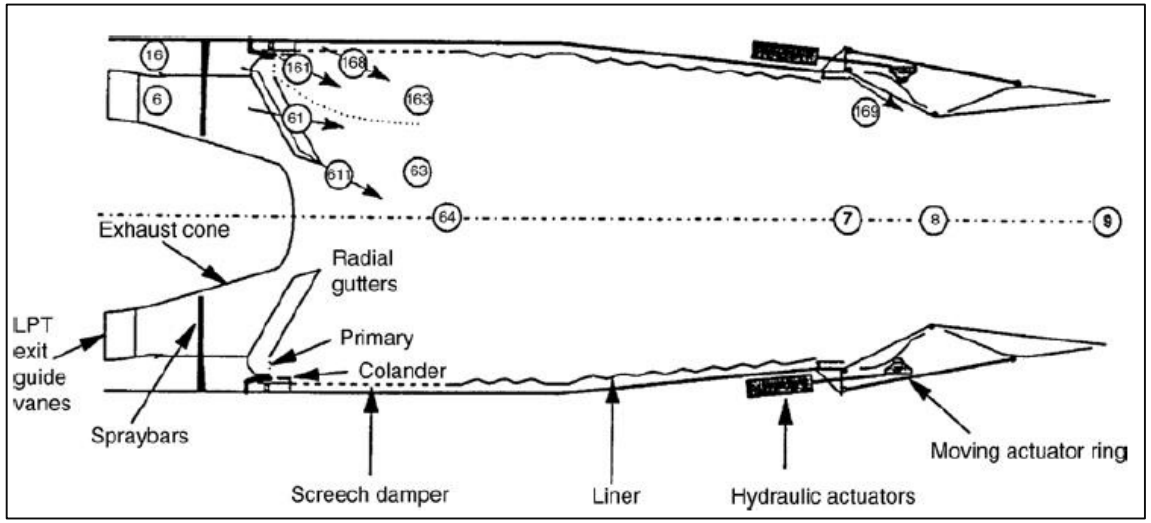
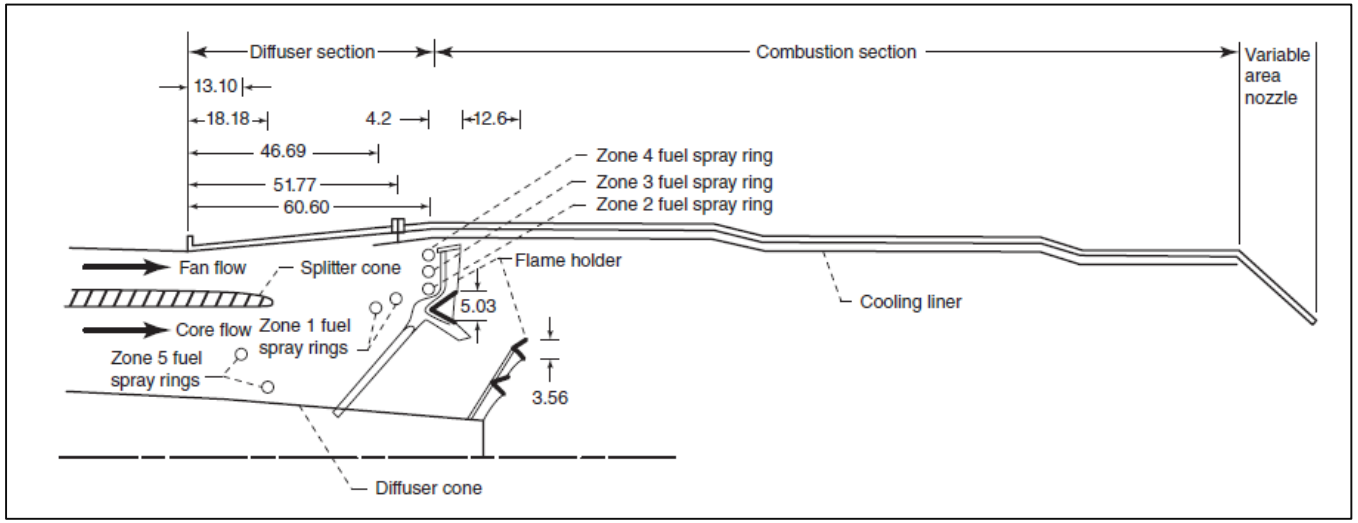
Afterburner Cross Sections



EJ200 afterburner and nozzle



TF30-P-3 afterburner

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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

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

$$\varepsilon_g = 1 - \exp\left[-290PL(ql_b)^{0.5}T_g^{-1.5}\right]. \qquad L = 336/H^2$$

$$l_b = 0.6D_L$$

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

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

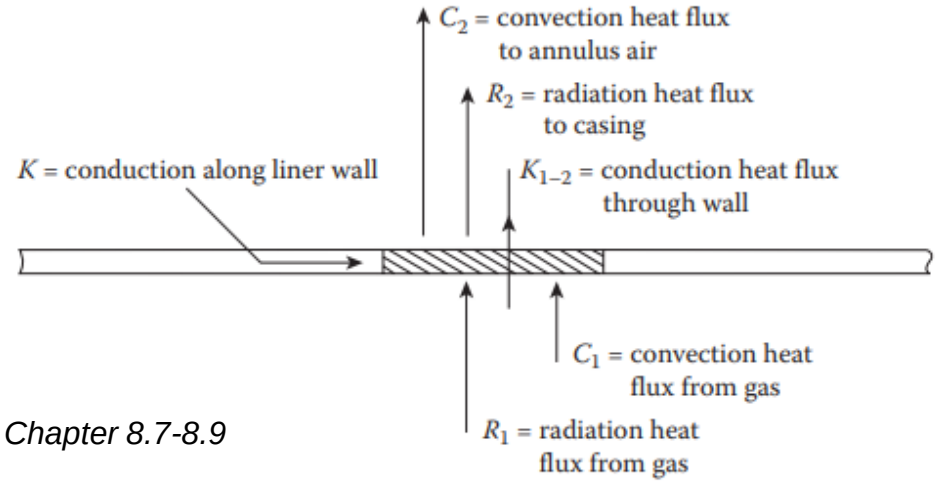
$$d_{h1} = 4\frac{\text{Cross-sectional flow area}}{\text{Wetted perimeter}} = D_L.$$

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

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

Energy Balance

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



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.

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

Internal Radiation

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

$\varepsilon_w = 0.7$,

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

$L = 1.7$,

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

$q = 0.0588$,

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

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

External Radiation

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

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

Internal Convection

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

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

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

$\dot{m}_s = \rho_a U_a A_s = 0.289\ \mathrm{kg/s}$.

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

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

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

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

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

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

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

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

$q_{pz} = 0.05$,

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

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

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

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

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

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

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

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

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.

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

External Convection

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

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

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

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

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

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

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

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

Metal Conduction

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

Result

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

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

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

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

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

Example is taken from Gas Turbine Combustion Alternative Fuels and Emissions (Lefebvre-3rd Edition) – Chapter 8.7-8.9
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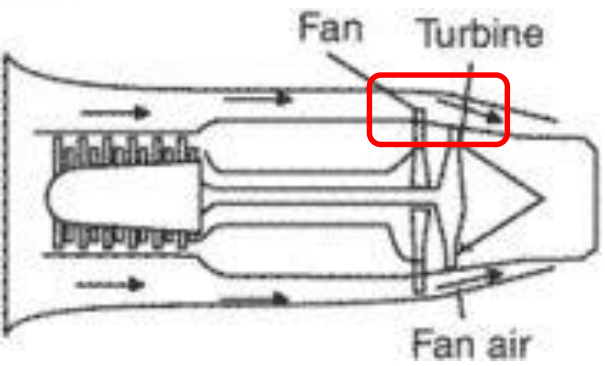
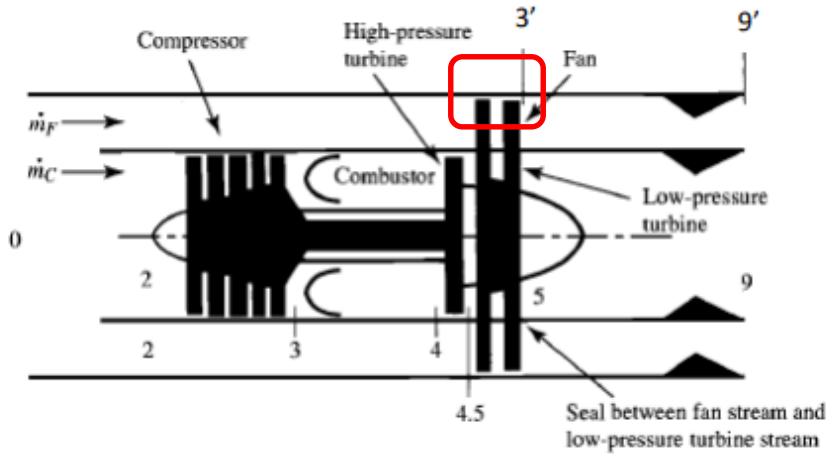
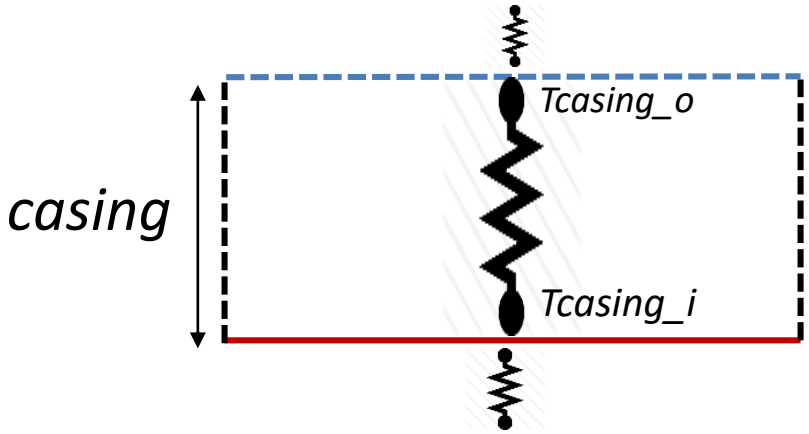
1D Heat Transfer Calculations of Casing





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



Fan Flow

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

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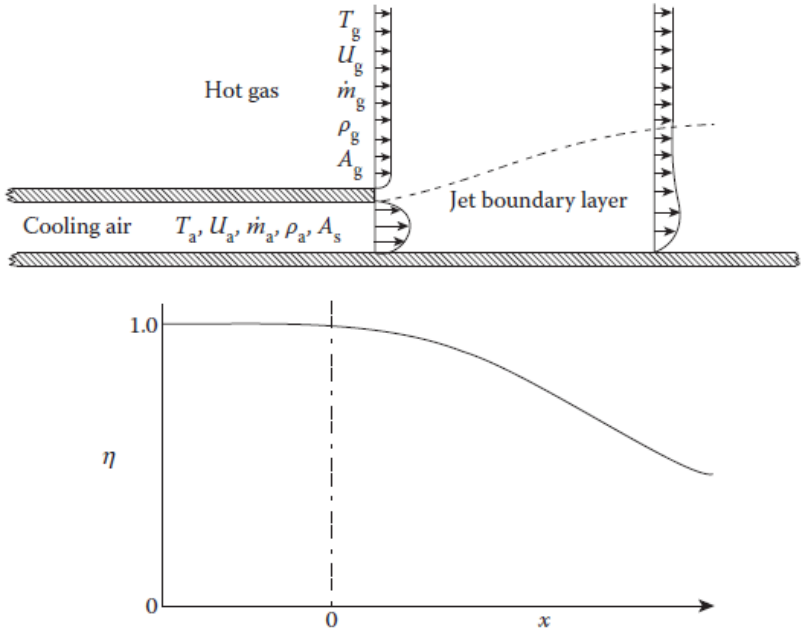
Cooling Design – Film Cooling

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 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 below 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:

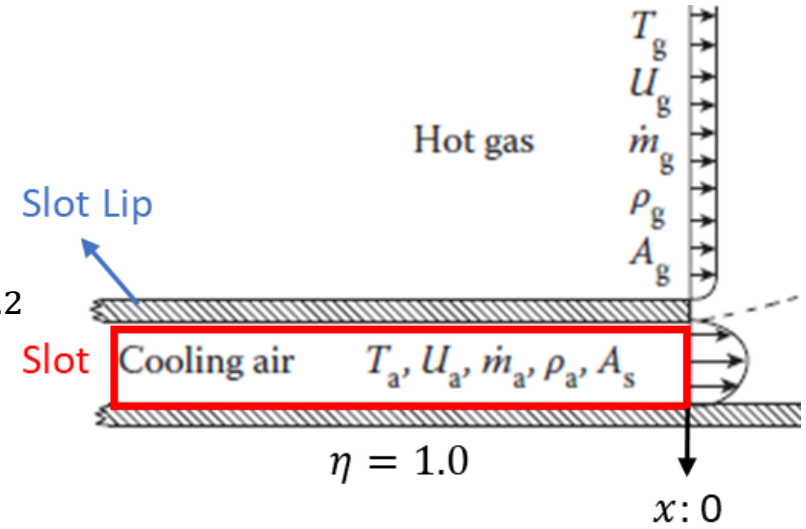
$$\eta = 1.1 m^{0.65} \left(\frac{\mu_a}{\mu_g}\right)^{0.15} \left(\frac{x}{s}\right)^{-0.2} \left(\frac{t}{s}\right)^{-0.2}$$

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)]

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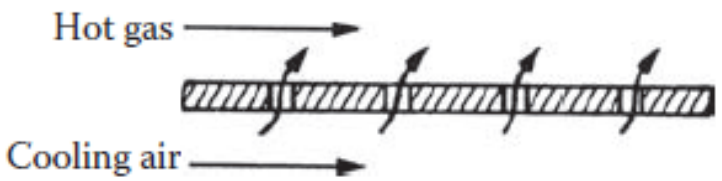
Cooling Design – Effusion Cooling

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

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

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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

ξ_0	η_0	a^*	c^*
9	5.8	4	0.24

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

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

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

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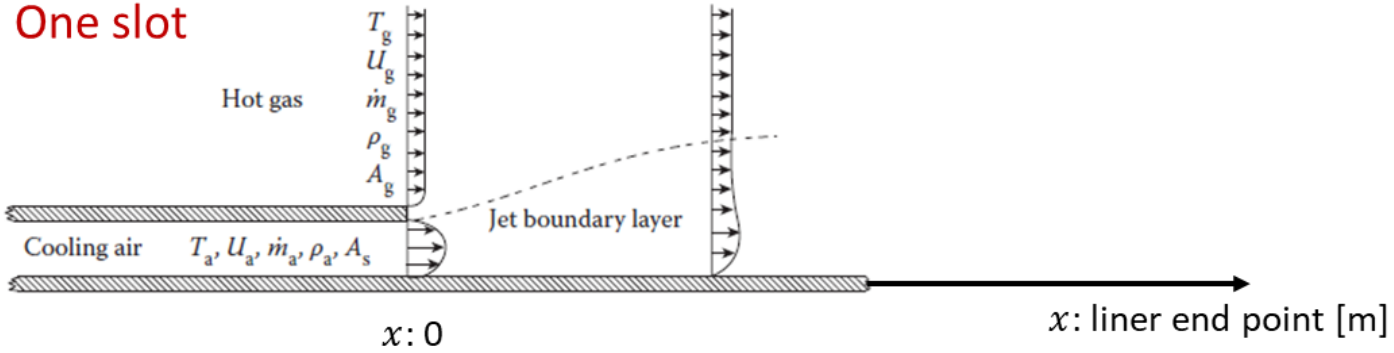
Cooling Design – Application: Film Cooling

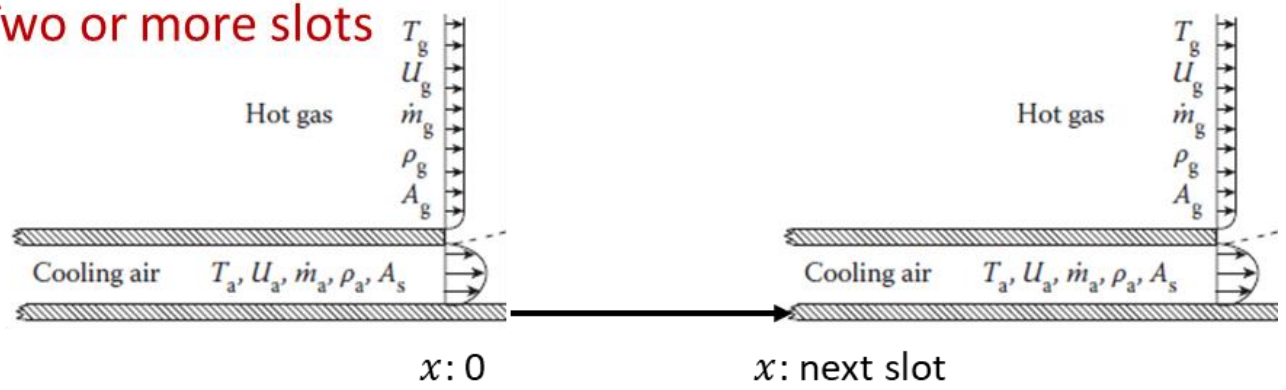
One slot: Effectiveness will be taken as 1.0 in the slot and 20 locations will be calculated from slot end point (x = 0) to liner end point (exhaust location). Then, these 20 points will be averaged and taken as area average adiabatic wall temperature.

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



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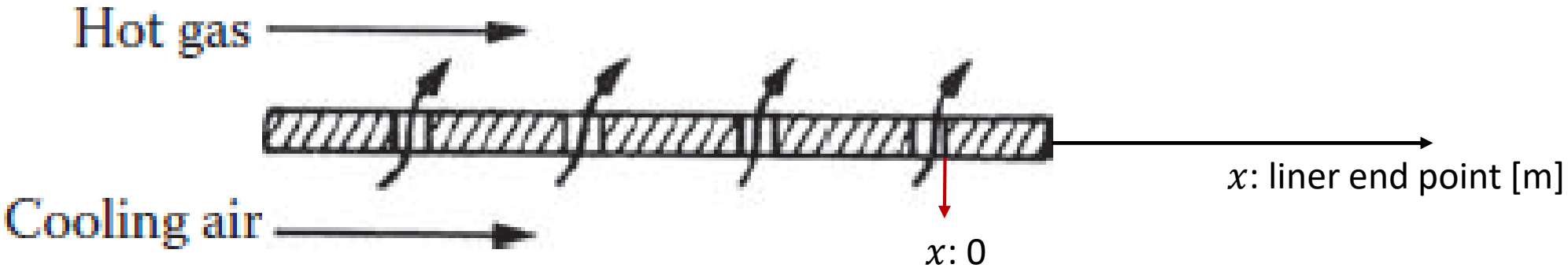
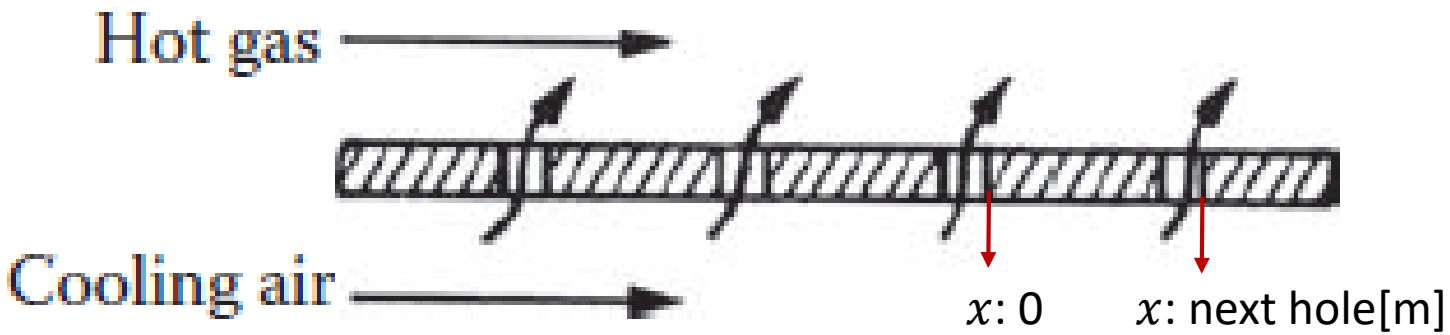
Cooling Design – Application: Effusion Cooling

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.





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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
- 1D hand calculations for preliminary liner and cooling designs
- 1D Thermal data both for casing and liner. (2D temperature distributions can be calculated)

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

THANK YOU

TASNİF DIŞI

TUSAS ENGINE INDUSTRIES INC.

Art Yakıcı (Afterburner) Yapısal Analiz Teknik Rehber
08.12.2022

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TASNİF DIŞI

Art Yakıcı (Afterburner) – Kavramsal Tasarım Raporu

Serbest Cisim Diagramının Çizilmesi	Aero,Thermal,SAS vb. yükler ve sınır koşulları serbest cisim diagramı yardımıyla detaylı olarak açıklanmalıdır.
Normal Operasyon Gerilme Hesaplamaları	Normal operasyon yükleri altında parçanın akma dayanımının altında kaldığı gösterilmelidir. Basit el hesapları kullanılabilir, 2B analiz + olarak değerlendirilecektir.
5G Altında Manevra Yükünün Hesaplanması	Doğrusal manevralar altında (X,Y,Z) parçanın kendi ağırlığından kaynaklı doğacak yük miktarı hesaplanmalıdır. Serbest Cisim Diagramında yükün nereden etkiyeceği gösterilerek açıklanmalıdır.
Manevra Altında Integrity Hesabı	Manevra yükü normal operasyon yüklerine eklenmelidir. Kriter olarak çekme dayanımı kullanılmalıdır. 2B analiz + olarak değerlendirilecektir.

Önemli Notlar

Modal Analiz	Parçanın modal analizini gerçekleştirerek sonuçların yorumlanması ve komponent tasarımlarında modal analiz yapmanın önemini detaylı olarak açıklayan ekiplere bonus puan verilecektir.
Malzeme Özellikleri	Malzeme özelliklerinin sıcaklık ile değiştiği göz önünde bulundurulmalıdır.
Gerilme Hesaplamaları	2B analiz sonucu raporlanan gerilme değerinin türü ve neden bu türün seçildiği açıklanmalıdır. El hesaplamaları parçanın en kritik bölgesi için gerçekleştirilmeli ve bu bölgenin yapısal anlamda neden en kritik olduğu açıklanmalıdır.
İyileştirme Çalışmaları	Ana boyutlandırma sonrası gerçekleştirilen yapısal hesaplamalar neticesinde tasarım iterasyonu gerçekleştirilir ise bu süreci, yapılan değişiklikleri ve sağladığı katkıları açıklamak + olarak değerlendirilecektir.