International Spring School on Forefront Alloys and Advanced Materials for Extreme Conditions

15 – 17 May 2017

Sardinia, Italy

Material developments for space applications

Prof.P.Bárczy, ADMATIS

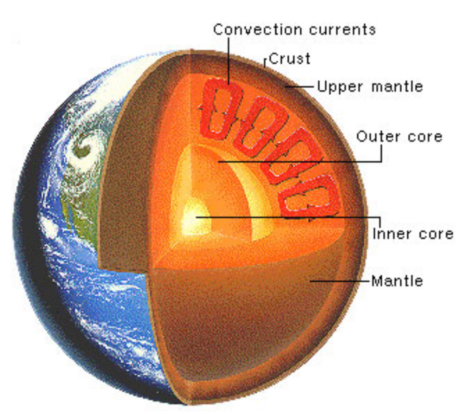
Admatis
Advanced Materials in Space

Table of Contents

Admatis
Advanced Materials in Space

1. Materials development

1.1 Natural materials



- Earth was a liquid sphere before 5 billion year
- Atomic interactions during solidification of earth's crust
- The first solid parts in the earth crust are 3 billion year old
- Due to its very slow cooling rate (10^{-6} K/year) atoms are assumed achieved their near equilibrium state
- Results: dilute mixtures (minerals), enriched compound parts (lode), occasionally some gem (diamond)
- High purity materials are very rare in the earth's crust
- Consequence: single phase materials are not stable

1.3 Artificial materials

Producing artificial materials there are two main steps:

(A) Extracting, purificating (or synthesize) row materials to produce high purity elementary materials (Cu, W, Si etc) (metallurgy and chemistry)

(B) Compose artificial materials mixing more elements in order to generate special properties (materials science and engineering)

1.2 Natural material: Basalt

- One of the oldest material, Basalt, typical material of mantle. Crystalline structure solifidicated during million years
- Typical composition

  Main elements: O, Fe, Mg, Si, Ti, Al, Ca, K, Na

  Trace elements: Sr, Nd, Hf, Os, Eu
- Natural material, high stability
- Equilibrium? Yes. Multicomponent model ????

Columnar basalt
Szent György Hill, Hungary

1.3 Artificial materials

Results in step one: 114 atoms, 92 of these are stable. Their purity extends from 2N upto 6N, but certain semiconductor is produced around 9N.

Results in step two: about 500.000 artificial materials, with increasing trend. Experts calculate 6000 new materials pro year.   The normal way is to extend their usage in the world market and substituting the earlier versions.

1.4 Limits of modeling

ICARUS SUPERMAT

Thermodynamic equlibrium systems of atomic mixtures was described by Gibbs hundred year ago. Since that solubility condition, solid solution, segregation in function of temperature and concentration were determinded by almost all binary systems.

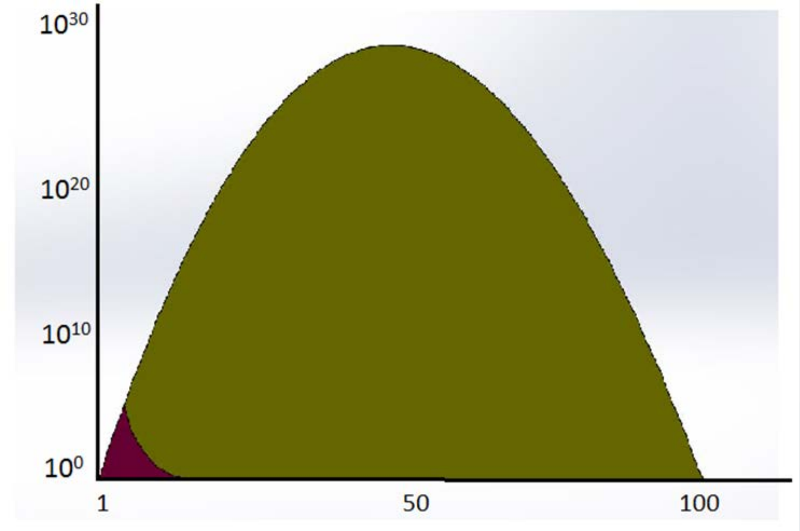
Some ternary and quaternary systems are also experimentally described
But model or description of equilibrium states of multicomponent systems are completly missing

Admatis
Advanced Materials in Space

1.5 Multicomponent systems

ICARUS SUPERMAT

Number of systems



Number of components

Unknow systems

Known systems

The number of phase diagrams in function of components increases fearful. Having 50 components there are 10^{28} possible systems - all are unknown.

1.6 New materials

- Driven by the business new materials with more and more components appear on the world market
- High tech means extended usage of more sophistic new materials with better properties
- Materials engineering developed its innovation methods – mostly far from fundamental sciences

1.7 Metals

	C	Cr	Ni	Mo	V	Si	Mn	Al	Ti	Co	W	Zr	B	Ta	Nb	Fe	component
E460	0.2					0.6	1									97.5	4
CrMoV steel	0.3	1	0.5	1,2	0.2											96	6
A286	0.08	15	25	1.2	0.2			0.3	2							56	8
Udimet720	0.03	15	55	3				2.5	5	14	1.2	0.03	0.03				10
IN738	0.1	16	61	1.7				4.3	3.5	8.5	2.6	0.1	0.01	1.7	0.9		12

Compositions of unalloyed steel, machine steel, rostfrei steel, reactor material, turbine blade alloy. More components, more specified requirements, higher prices.

1.8 Ceramics

Oxide	S %	A %	N %	K %	P %	Ce %	M %	B %	C %	Z %	T %	Components
Quartz	100											1
S glass	65	25					10					3
E glass	54	14	1			20	0.5	8				8
EAM140	54.8	14.1	8.4	10.6	3.9	0.8	0.2	0.3	4.9	1.0	0.3	11

Oxide	Code
SiO_2	S
Al_2O_3	A
Na_2O	N
K_2O	K
P_2O_5	P
CeO_2	Ce

Oxide	Code
MgO	M
B_2O_3	B
CaO	C
ZrO_2	Z
TiO_2	T

Transparent ceramics from window glas toward optical fibres and microscope lenses.

1.9 Polymers

Plastics	Components
Packaging films	3
Jar rubber	9
Mattress	14
Branded sport shoes	25
Formula1 tires	230

Polymer materials from simple packaginig films toward the most unique tire family

2. Space environment

2.1 Space properties

- high vacuum
- high radiation
- atomic oxigen
- particle and debris collision danger
- outgassing, condensation
- temperature cycles
- microgravity

2.2 Space characteristics

ICARUS SUPERMAT

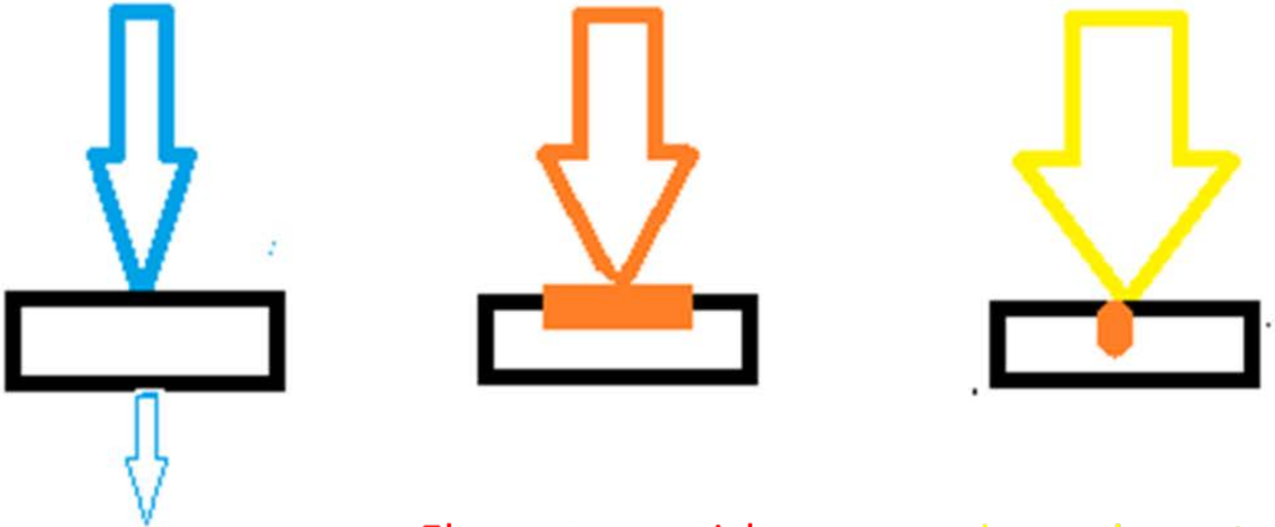
Altitude (km)	Pressure (mmHg)	Kinetic temp (K)	Gaseous density (particle/cm^3)	Composition	UV radiation	Particle radiation (particle/cm^{3}s)
sea level	760	±300	2.5×10^{19}	78%N_2 31%O_2, 1%AO	section of solar spectrum 0.3	-
30	10	-	4×10^{17}	N_2, O_2, AO	absorption zone	-
200	10^{-6}	±1200	10^{10}	N_2, O_2, O, O^+	full solar spectrum	-
800	10^{-9}	±1300	10^{6}	O, He, H, O^+	full solar spectrum	-
6500	10^{-13}	-	10^{3}	H, H^+, He^+	full solar spectrum	10^4 proton 35MeV 10^4 electron 40keV
22000	10^{-13}	-	10^{1} -10^{2}	85% H^+ 15% He^+	full solar spectrum	10^8 proton 5MeV 10^8 electron 40 keV 10^4 electron 1.6 MeV

Admatis
Advanced Materials in Space

2.3 Sublimation in high vacuum

	Al	Cr	Fe	Ag	W	Re	Ir	Au	Pb
atomic number	13	24	26	47	74	75	77	79	82
100nm/year at C°	550	750	770	480	1880	1820	1300	660	270
1mm/year at C°	810	1000	1050	700	2500	2300	1740	950	430

2.4 Radiation interactions in space



Admatis
Advanced Materials in Space

2.5 Space radiation categories

Radiation	Mass,g	Velocity, m/s	Critical dozis	Relevant material property
Electromagnetic radiation (UV, X Ray, γ)	0	$3x10^8$	∞	μ/ϱ, mass attentuation coeff
β (electron)	10^{-31}	10^6	10^{18}/s,mm^2	Ω, electrical resistance
particle (proton, neutron, α, heavy ion)	10^{-27}	10^4	10^{18} /cm^2	neutron mass absorption coefficiens
debris	1μm – 10^{-12} 1mm - 10^{-3}	1-10	1	Fracture thougness, elongation

2.6 Space radiation components

- **Solar-particle events**
  - -occur sporadically, not predictable
  - -solar-flare events may last four or more days
  - -dose depends on orbital altitude
- **Galactic cosmic radiation**
  - \- 85%protons, 13% α particles, 2% heavy nuclei
  - \- integrated yearly particle fluence: 10^8protons/cm^2
  - \- yearly radiation dose: 4-10 rads
- **Geomagnetic trapped radiation**
  - \- primary electrons and protons

Admatis
Advanced Materials in Space

2.7 Radiation absorbance

ICARUS SUPERMAT

MeV	mass attentuation coefficient, μ/ϱ, cm²/g										
	B 5	Al 13	Ti 22	Cr 24	Fe 26	Ag 47	Gd 64	Hf 72	W 74	Au 79	Pb 82
0,01	1	26,3	100	105	178	100	200	100	58	100	80
1	0,06	0,06	0,08	0,1	0,08	0,06	0,06	0,08	0,065	0,08	0,07
100	0,01	0,02	0,036	0,04	0,04	0,06	0,08	0,09	0,088	0,09	0,093

Admatis
Advanced Materials in Space

2.8 Particle absorbance

proton-neutron interaction parameters											
	B 5	Al 13	Ti 22	Cr 24	Fe 26	Ag 47	Gd 64	Hf 72	W 74	Au 79	Pb 82
neutron cross section	755	0,23	6,1	3,1	2,5	63,6	49700	104	18	98,6	0,17
neutron mass absorption	2,4	0,03	0,004	0,002	0,001	0,02	7,3	0,02	0,003	0,017	0,00003

2.9 Debris size distribution on LDEF

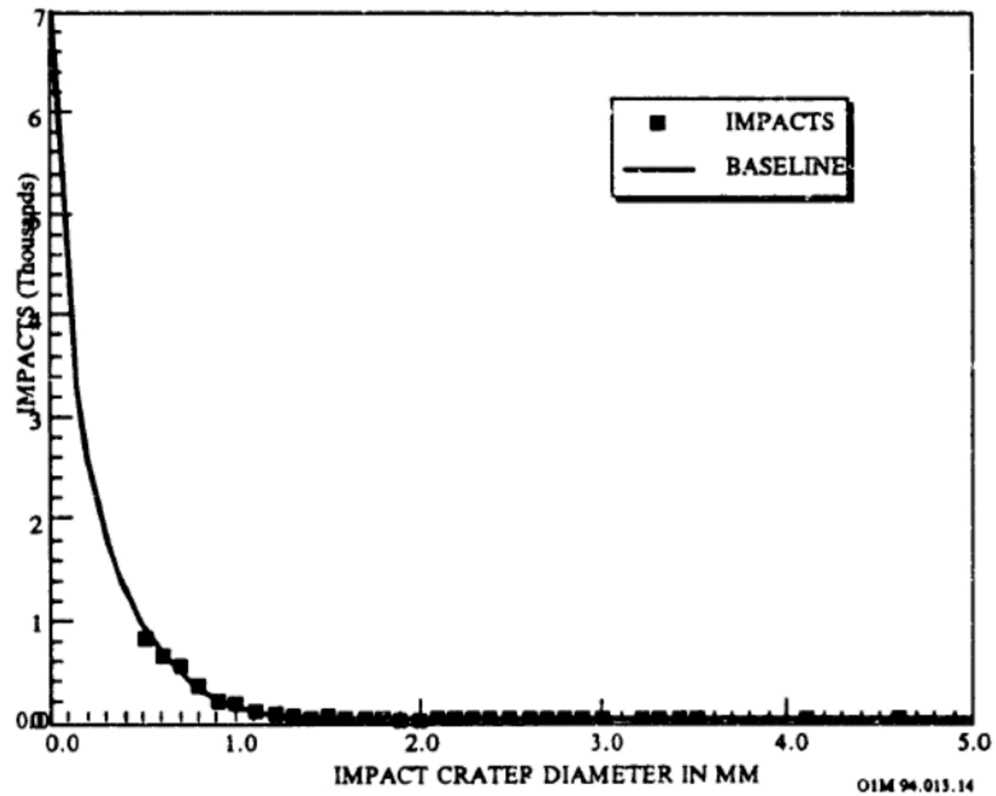
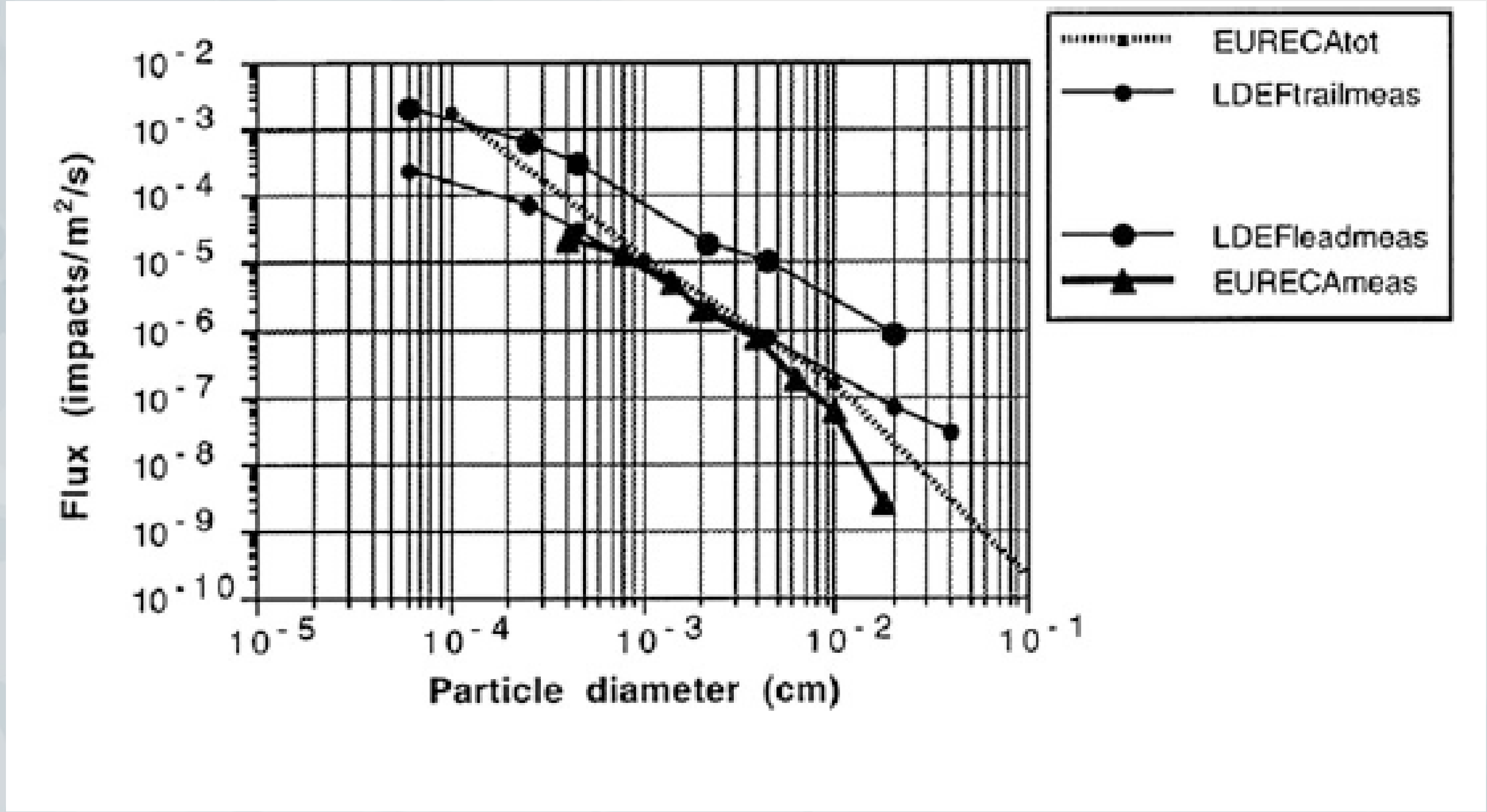


Figure 2- 26. Size Dependence of Impact Craters

Admatis
Advanced Materials in Space

2.10 Space debris



2.11 Radiation damage in space

- The most dangerous orbit is the geostacioner one
- here the particle fluence is 10^8protons/s/cm^2
- In one year the integrated particle amount can be $3x10^{15}$ / cm^2
- In steels of nuclear power stations the lowest dose of neutrons with 0.5MeV or more causing any change in mechanical properties occurs above 10^{18}neutrons/cm^2 [6]
- This is why the first structure destruction in satellite materials is not expected before 300 years

2.12 TANDETRON, ATOMKI

MTA Atomki has installed the new Tandetron accelerator in May 2014 made by High Voltage Engineering Europa BV. In January 2015 a Duoplasmatron ionsource with the injector magnet, then a simple temporary switching magnet was installed. The Tandetron accelerator needs negative ion input and then produces high energy positive ion beam (in this case protons). In the meantime we also installed a 9-port switching magnet directly at the exit of the Tandetron, i.e. to a temporaty position. We can accelerate 200 keV - 4 MeV energy protons with 25 µA beam current.

25µA= 1.5x 10^{13} proton/s/cm^2

200s exposition time is equivalent with one year on geostationer orbit

3. Metal behavior in space

3.1 Long Duration Exposure Facility, LDEF

- Weight: 10t
- Length: 9,1m
- Diameter: 4,3m
- Mission time:1984-1990

Experiments with more thousand materials samples on 86 tray

3.2 LDEF results [2]

ICARUS SUPERMAT

- **Thermal-optical properties** of bare and surface treated 6062 aluminium [2]

Sample	Position on LDEF	Exposure	Surface treatment	Solar absorptance	Thermal emittance
C03-5	Trailing edge back surface	No direct exposure	Bare	0.71	0.13
C03-5	Trailing edge	$2.6x10^{3}$AO/cm^{2} 11000 ESH	Bare	0.74	0.08
C09-7	Leading edge back surface	No direct exposure	Bare	0.72	0.09
C09-7	Leading edge	$9x10^{21}$AO/cm^{2} 11200 ESH	Bare	0.69	0.06
Control#4	Ground control	No space exposure	CAA	0.32	0.18
C03-6	Trailing edge	$2.6x10^{3}$AO/cm^{2} 11000 ESH	CAA	0.35	0.14
C09-2	Leading edge	$9x10^{21}$AO/cm^{2} 11200 ESH	CAA	0.33	0.17

AO – atomic oxigen, ESH – equivalent sun hour, CAA – chromated surface

3.3 LDEF results: atomic oxigen erosion [2]

ICARUS SUPERMAT

Metal	AO reactivity $10^{-26} cm^3/atom$	Accomodation of AO per 10^4 incidents	Comments
Copper	0.87	3.6	
Molybdenum	0.14	2.8	
Tungsten	0.044	1.0	
HOS 875	0.29	2.5	
Tophet	0.55	5.0	
Tantalum	0.60	8.3	
Titanium 75A	0.39	4.4	
Mg AZ31B	0.45	2.0	
Niobium	0.14	2.0	
Silver disk fine grain	2.9	8.4	
Silver cold rolled	27.5	80.0	

3.4 LDEF results [2]

Thickness and surface composition of layers on metals, LDEF [2]

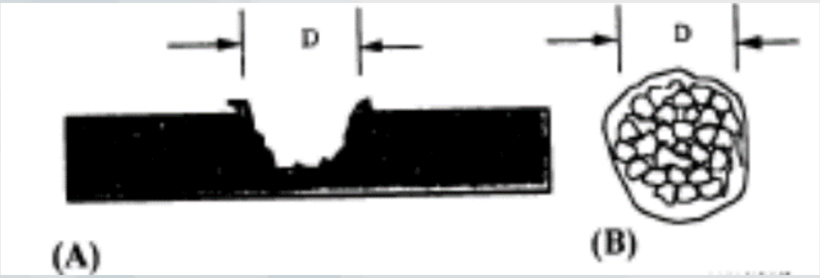
Sample	LDEF location	Space condition	Oxide	Thickness of oxide
Al	trailing edge	1.3x10^{17}atoms/cm^2 11100 ESH	$Al_2 O_3$	395
		shielded	$Al_2 O_3$	68
Cu	leading edge	3.33x10^{20}atoms/cm^2 4500 ESH	Cu_2O	1039
		shielded	Cu_2O	449
Ni	trailing edge	1.3x10^{17}atoms/cm^2 11100 ESH	NiO	687
		shielded	NiO	60
Ta	leading edge	9x10^{21}atoms/cm^2 11200 ESH	Ta_2O_5	505
		shielded	Ta_2O_5	31
Zr	leading edge	9x10^{21}atoms/cm^2 11200 ESH	ZrO_2	688
		shielded	ZrO_2	42

ESH – equivalent sun hour

ICARUS SUPERMAT

Space debris effects

- High velocity debris and micrometeorite are very dangerous for satellites



- During 5.7 year one debris of 0.7mm diameter with 10 km/s impact velocity penetrated through 2,5mm Al wall. This was one single case on 7squaremeter satellite surface
- But 7 smaller impact occured and penetrated through 1,5mm wall

4. Combustion chamber of rockets

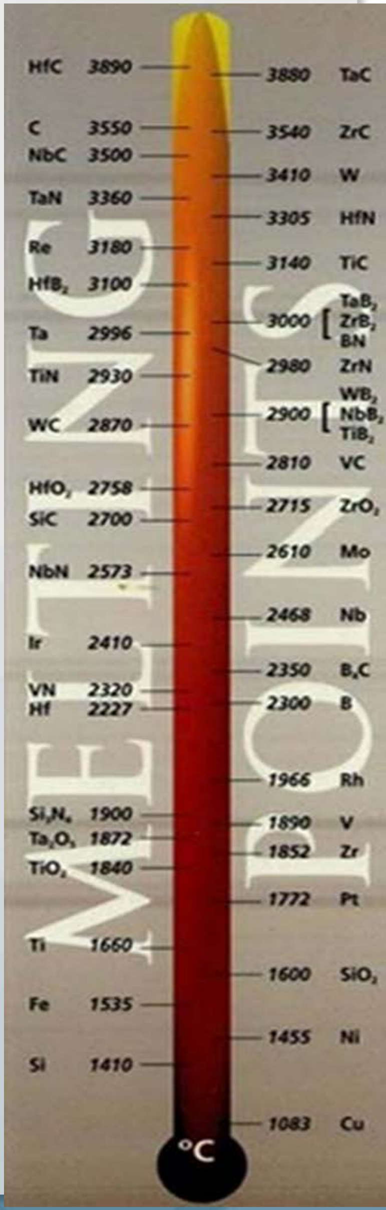
4.1 Objectives of ICARUS

To develop materials with stable nanocrystalline structure

- Stability means unchanged long term properties at higher temperatures
- Stability means unchanged long term properties in intensive radiative environment

4.2 Temperature range of space materials

- Space structural hardwares operate mainly at low temperature (-100 … +100 Celsius)
- There is one special field where the high temperature behavior is important - this is the world of combustion chambers (+500 …. +3200 Celsius)
- Other special field of space materials is the coatings of retrievable capsules but this is not actual in Europe today (RSA and US only)



4.3 Combustion chambers

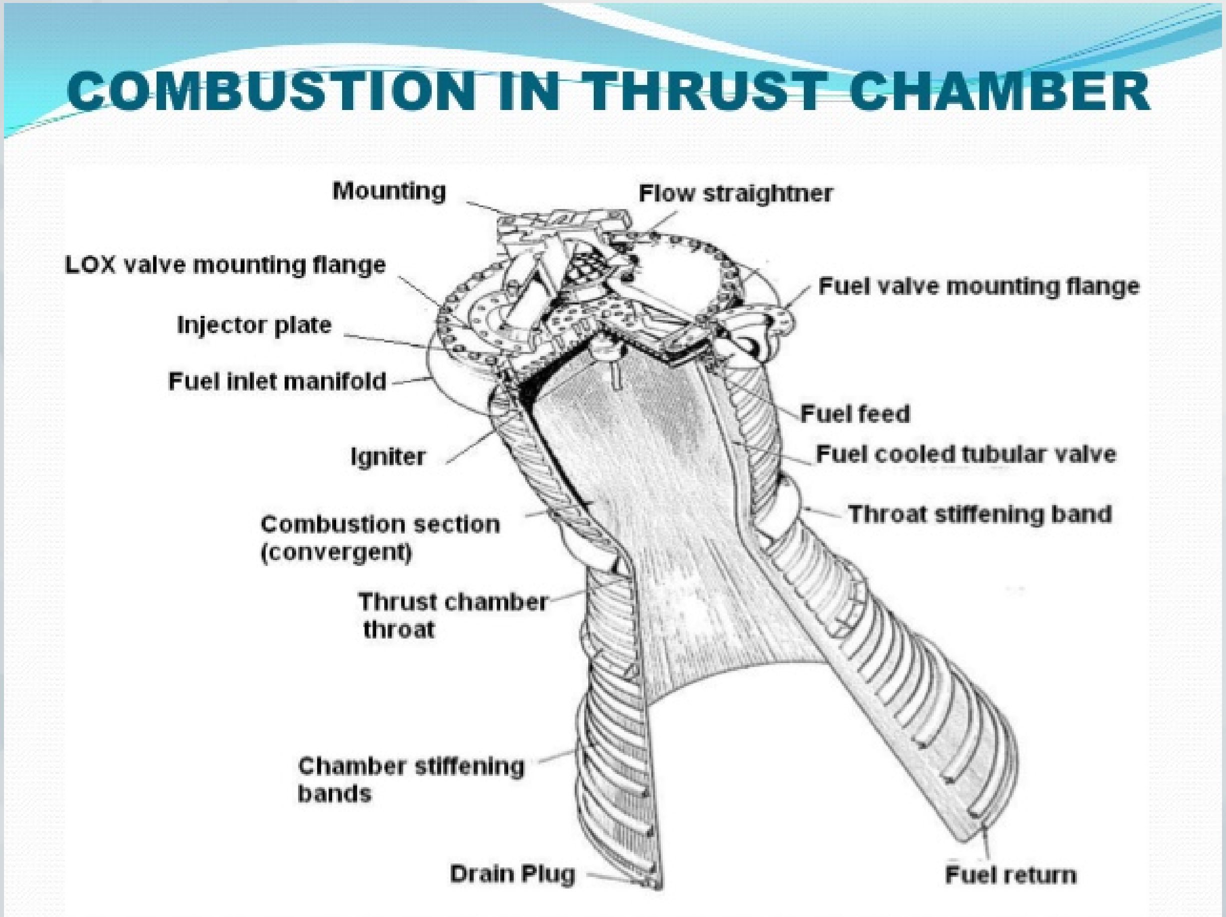
Combustion chambers are commons in each engines where chemical energy is transformed into mechanical energy. Aeropace industry uses rackets where thrust force is made by hot gases coming out from nozzle of combustion chamber

4.31 Liquid rocket engines (regenerative cooling, transpiration cooling)

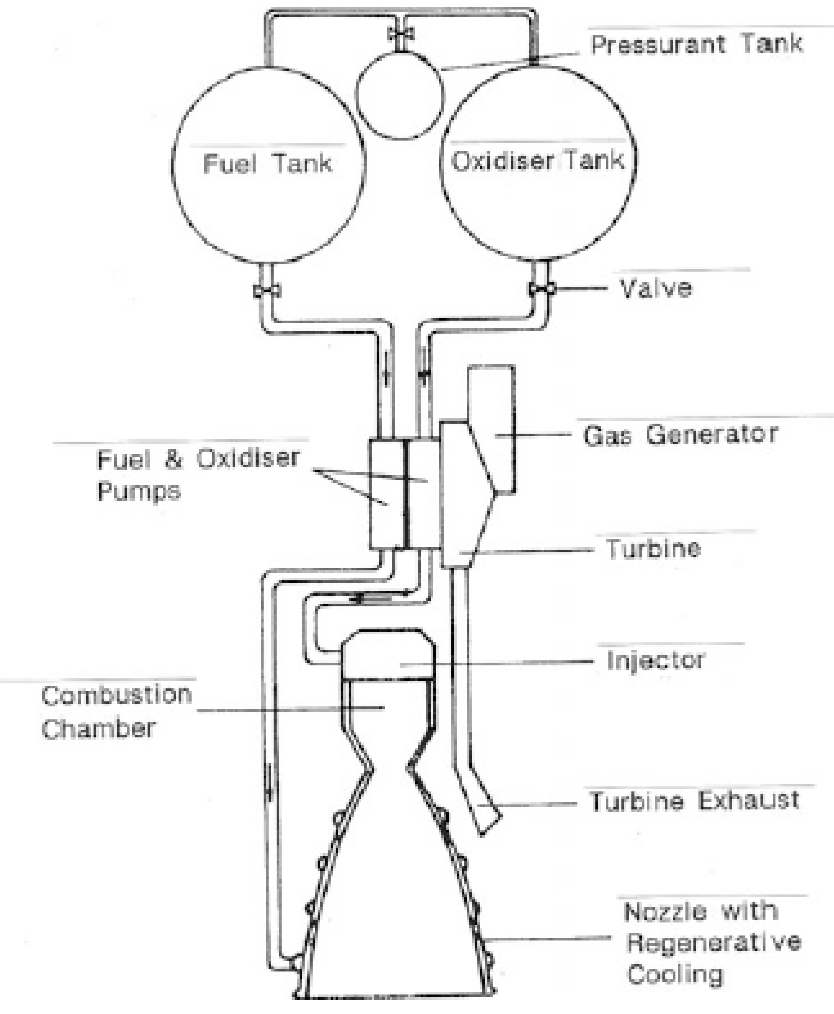
4.32 Solid rocket engines

4.33 Jet engines (turbines)

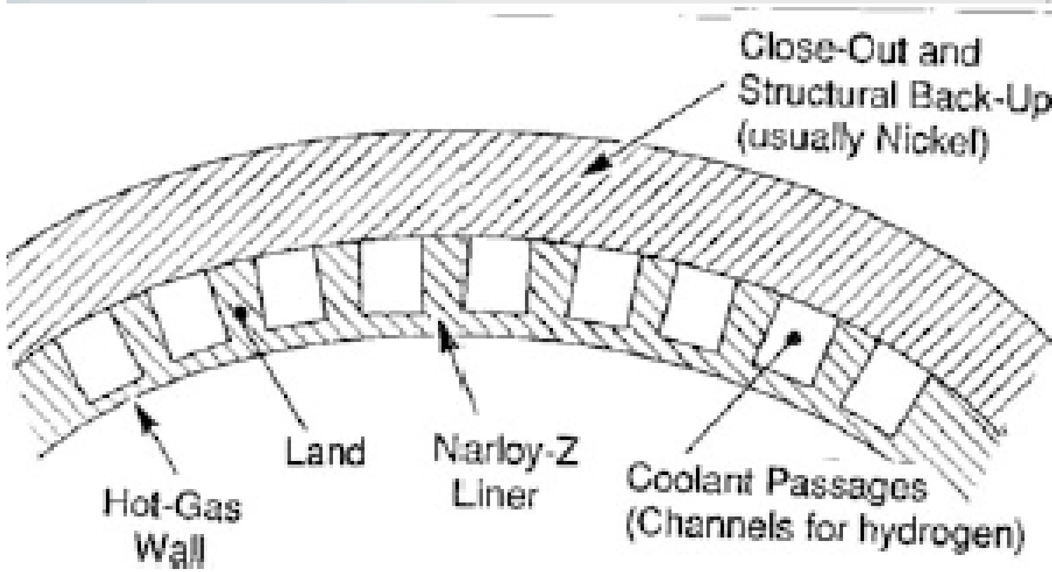
4.31-1 liquid rocket structure



4.31-2 Rocket engine with regenerative wall cooling[1]

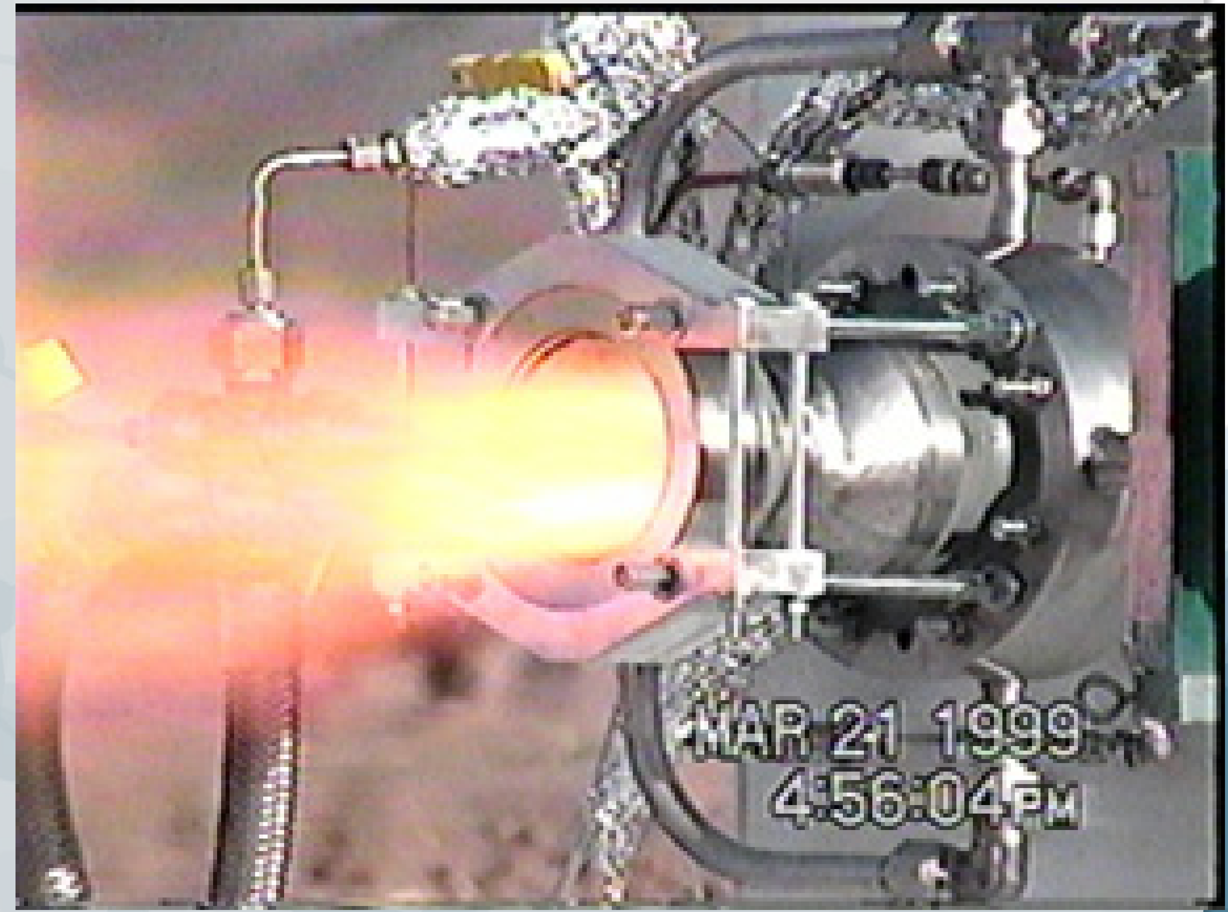


2.8 A liquid propellant rocket engine



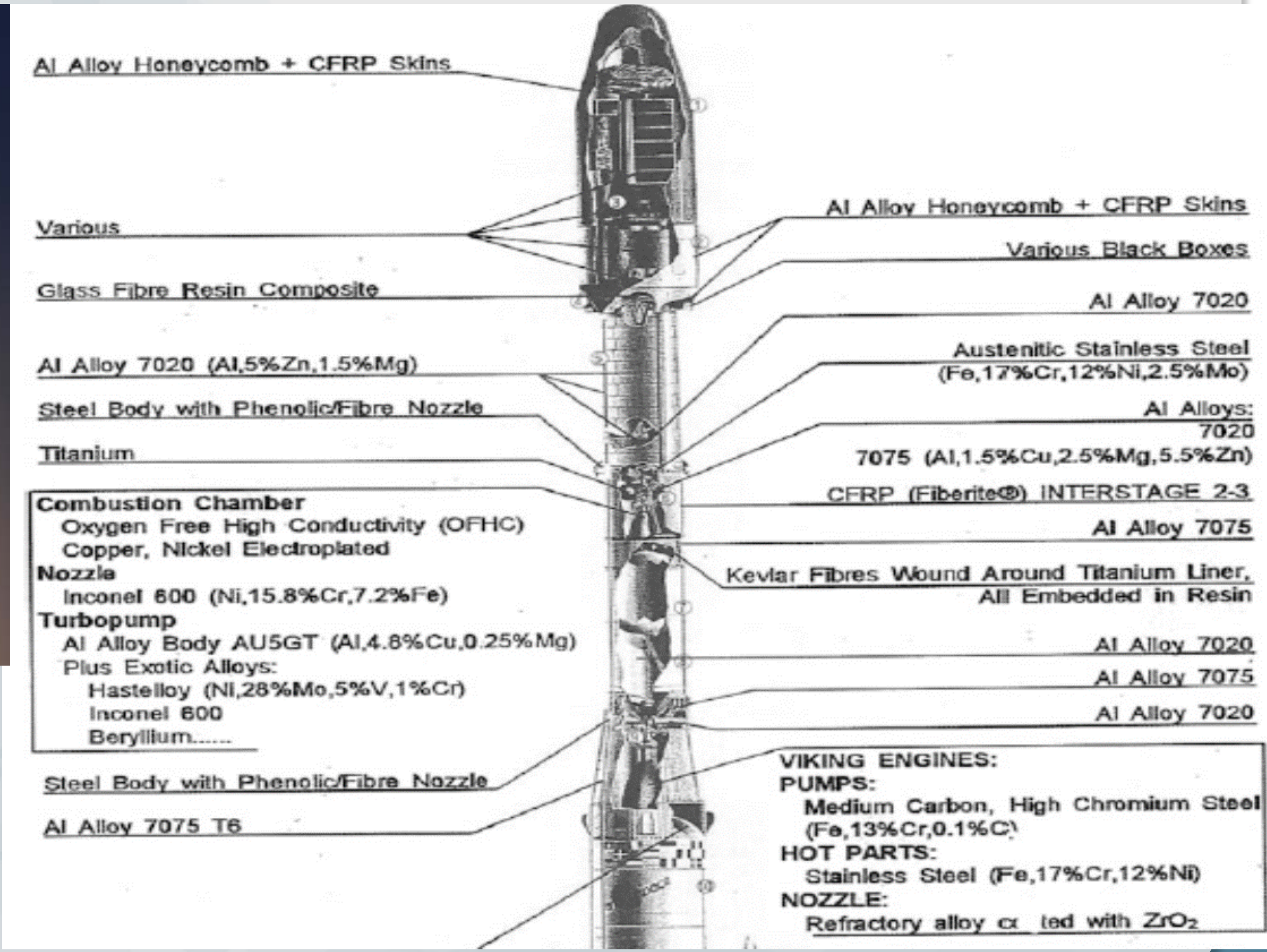
4.31-3 Regeneratively cooled systems [3,4,5]

- Material: Cu3Ag0.3ZrO, or stainless steel
- Temperature: 500-700C°
- Application: launchers



Admatis
Advanced Materials in Space

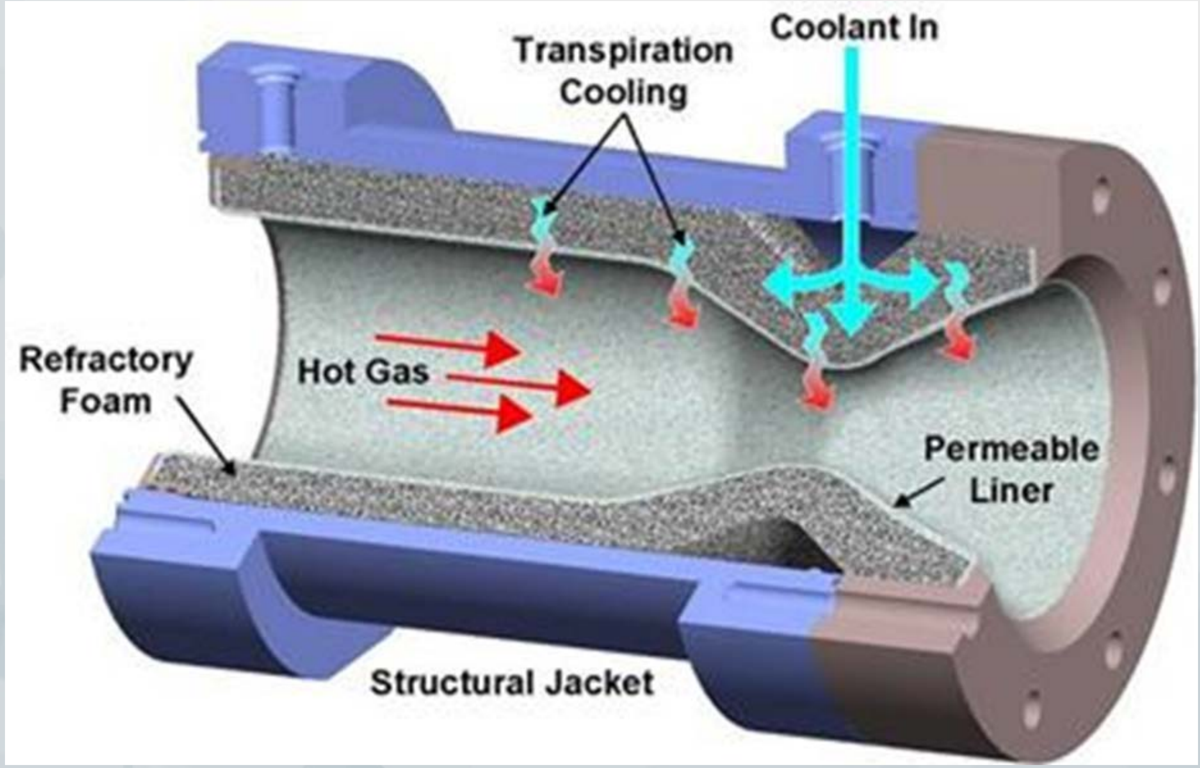
4.31-4 ARIANE IV



Admatis
Advanced Materials in Space

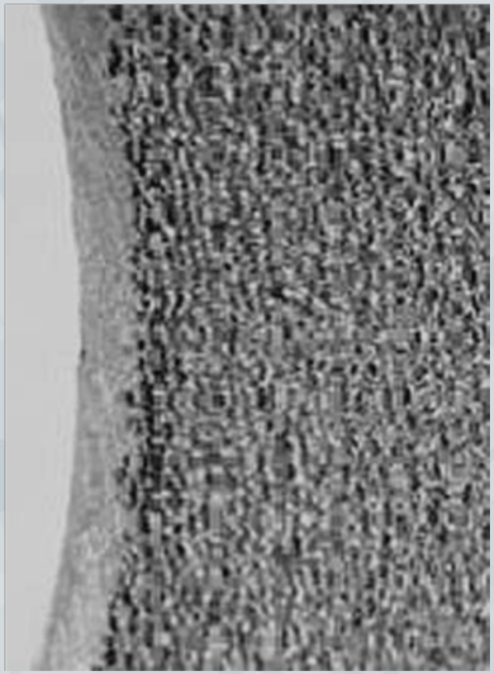
4.31-5 Transpiration cooled systems

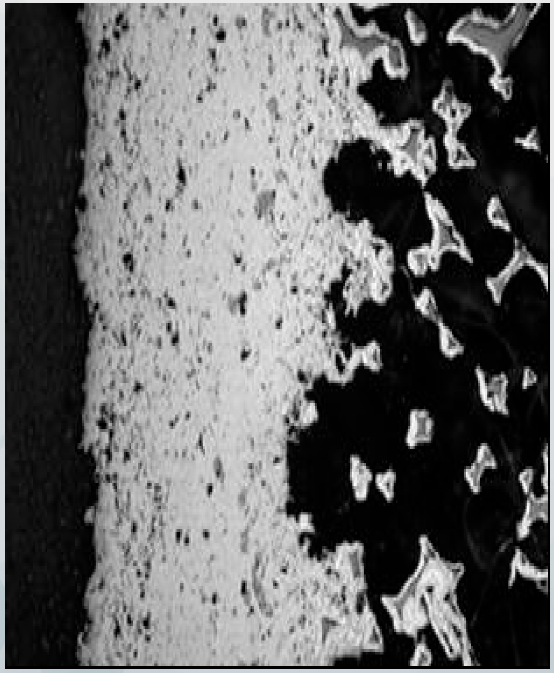
- Materials: Mo foam
- Application: missils



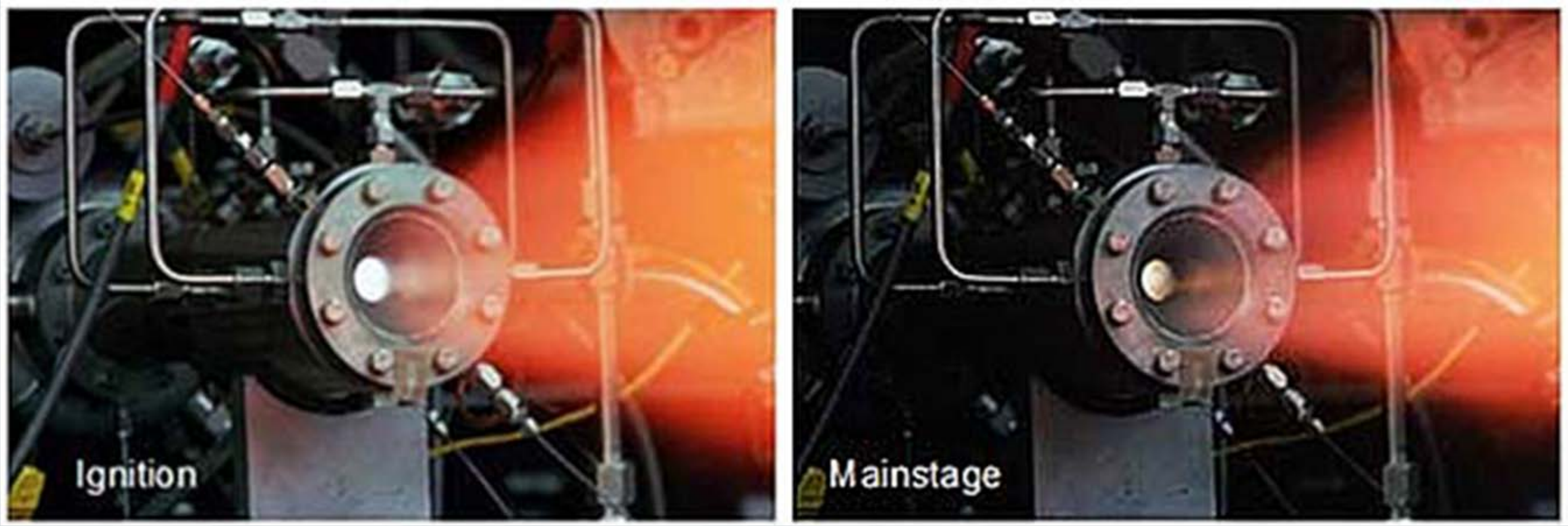
4.31-6 Transpiration cooled systems

- Wall material for transpiration cooled combustion chamber
- 80ppi Mo foam with porous open cell Mo liner





4.31-7 Transpiration cooled systems



- Transpiration-cooled molybdenum foam/porous molybdenum liner combustion chamber during oxygen/hydrogen hot-fire testing at NASA Glenn

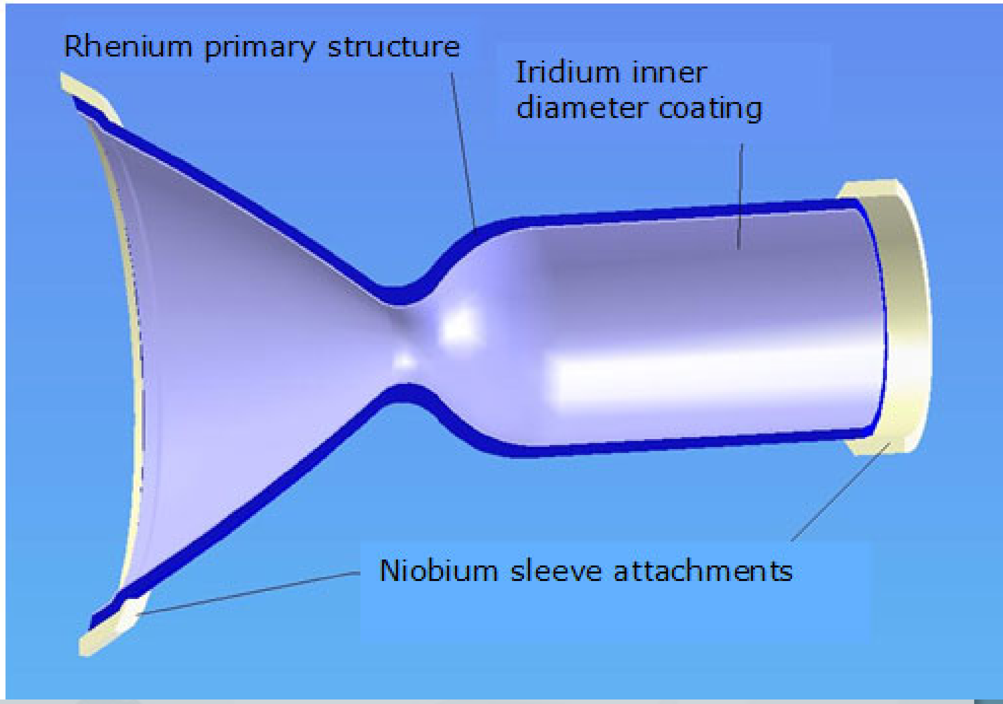
4.32-1 Solid Rocket Engines

- Thin wall Rhenium chamber upto 3300 C°
- Tungsten or C/C coated with Tungsten (CVD) above 3300 C°
- Ceramic (TaC, HfC) lined throats … above 3600 C°

4.32-2 Radiation cooled systems [3,4,5]

Materials:

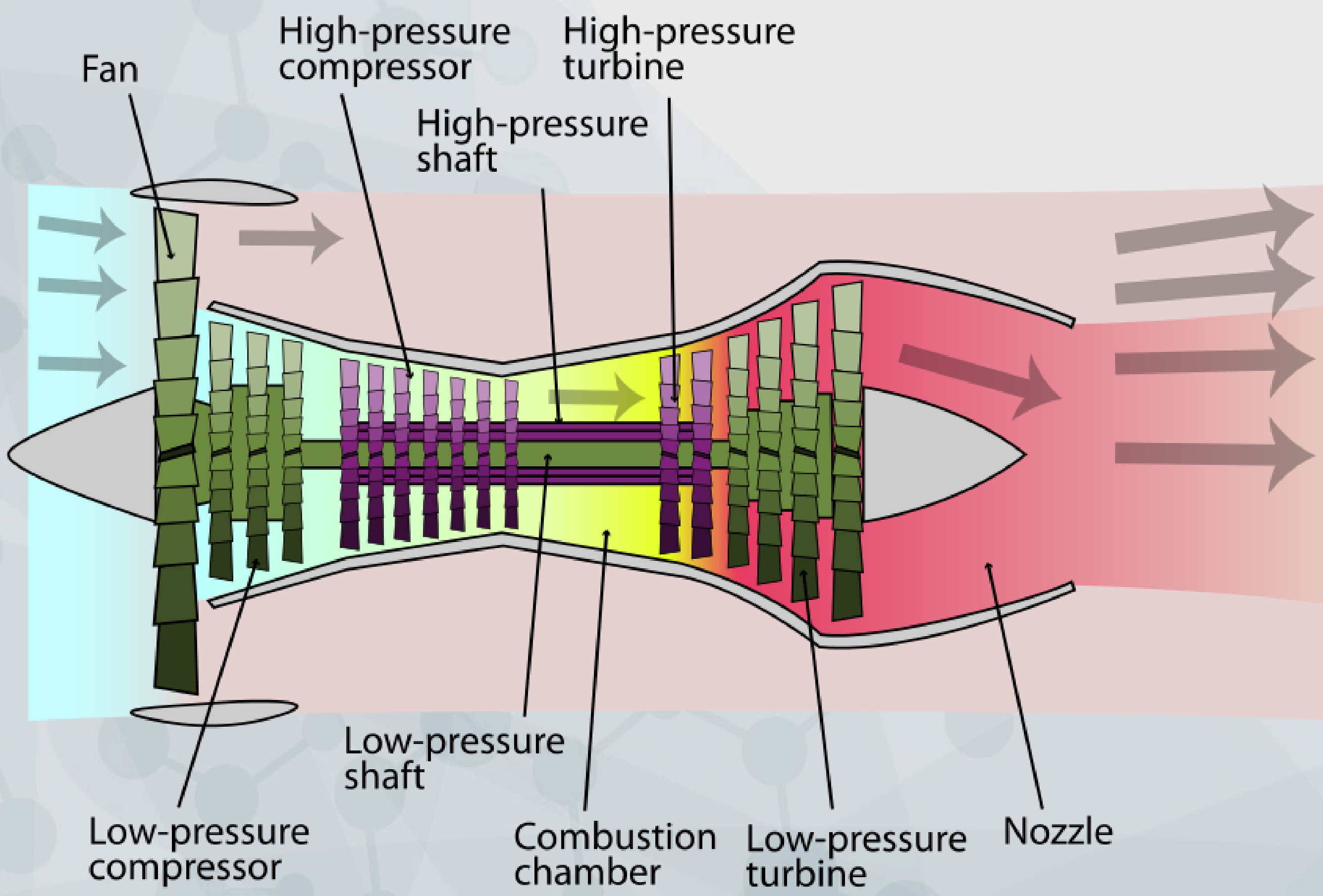
- Rhenium/Iridium,Niobium 2200 C°
- Oxide-Iridium/Rhenium hours at 2400 C°or many minutes at 2700 C°
- mixed Ir/Rhenium + C/C composite



Note: for spacecrafts on geostationer orbit

4.32-3 Radiation cooled systems[3,4,5]

4.33 Jet engine for airplanes



Thank you!

The ICARUS project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 713514.

The SUPERMAT project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 692216.