Pevné, pevnější, nejpevnější

Aleš Materna

Katedra materiálů FJFI ČVUT

The World Is Not Enough (1999)

lanko: nosnost 800 liber (363 kg), délka 50 stop (15 m)

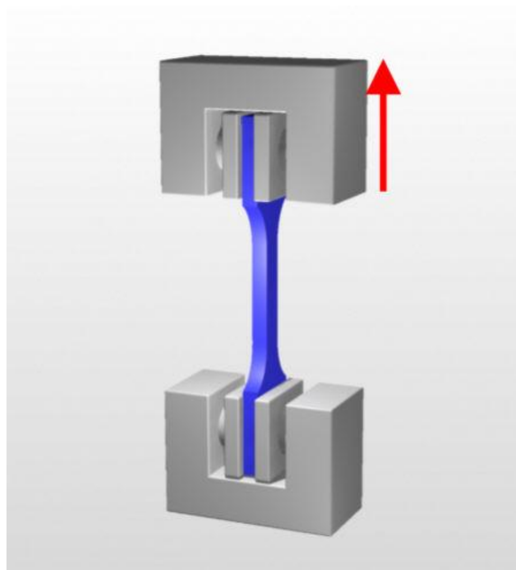
Jakou pevnost musí mít materiál lanka?

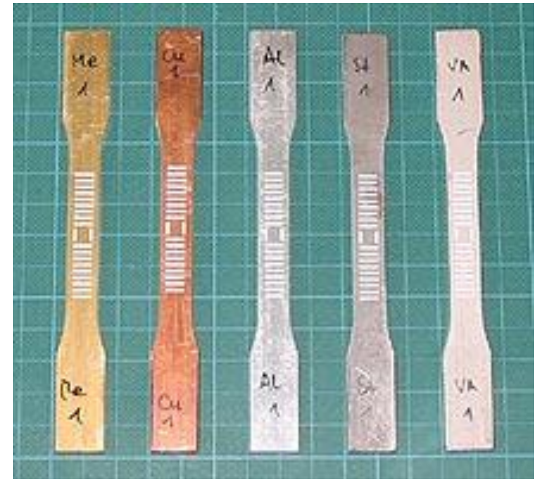
hodinky: Omega Seamaster (⌀ 41 mm, tl. 10 mm) → 13 200 mm^3

Předpokládejme, že lanko vyplňuje 50% objemu hodinek. Potom průřez lanka bude $S = 6600/15000 = 0{,}44$ mm^2.

Pevnost materiálu $R_m = F_{max}/S = 363 \times 9{,}81$ N$/0{,}44$ mm$^2 \approx$ **8 GPa**

Zkoušky pevnosti



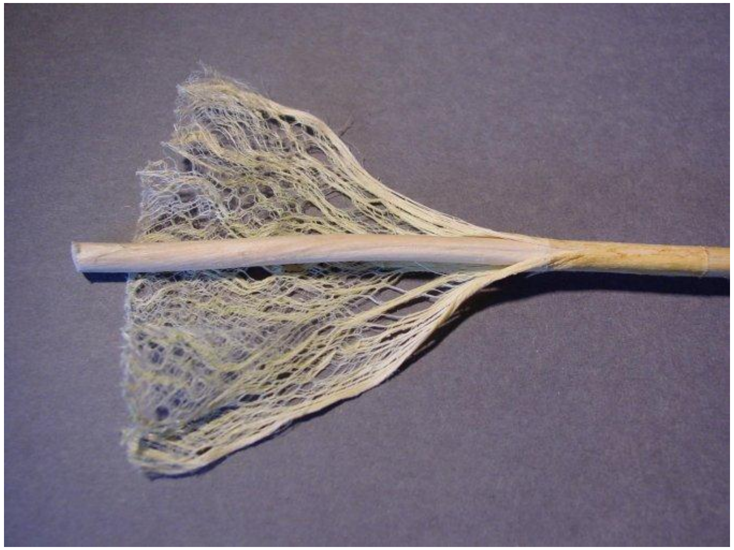


Konopné vlákno

pevnost: 0,3 – 0,4 GPa

+ pevné
+ velice dobře odolává povětrnostním vlivům

− pěstování



Hedvábné vlákno

pevnost: až 0,6 GPa

+ vlákna jsou velice tenká (10 μm) a dlouhá (kokon je tvořen jediným vláknem dlouhým stovky metrů)

Pavoučí vlákno

pevnost: až 1,7 GPa

+ pevné, ale přitom velice pružné (30-40%)
+ tenčí než lidský vlas
+ s tvarovou pamětí
+ recyklovatelné

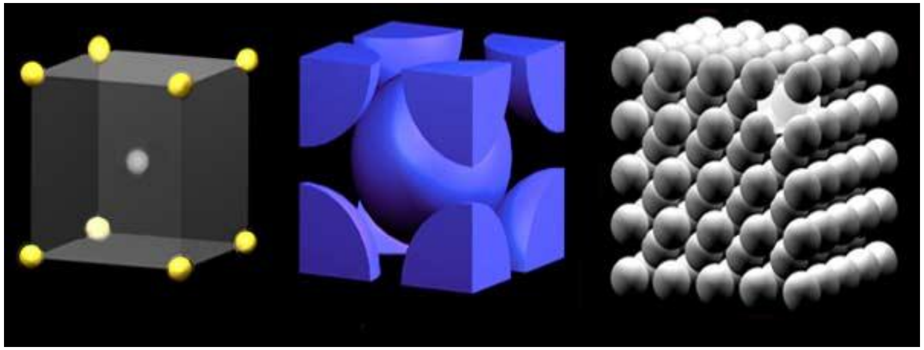
– velice obtížná výroba ve velkém

Ocel

mez pevnosti:
2 GPa
hustota:
7850 kg m^{-3}

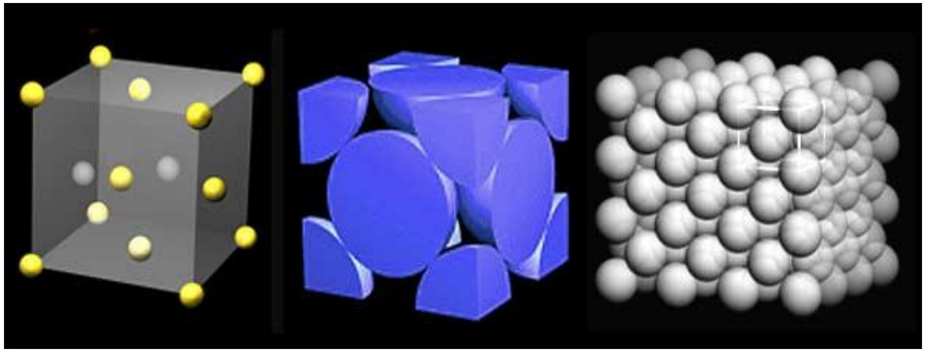
ocelové lano (cca 1834)

Čím je dána pevnost kovových materiálů?



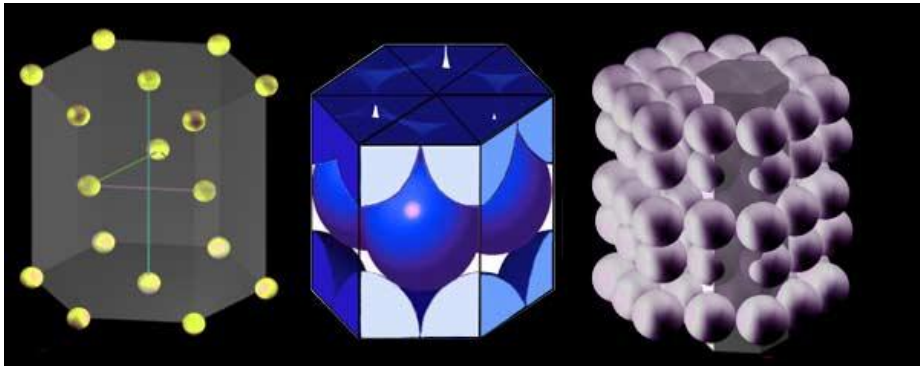
BCC mřížka

Fe, Ti, W, Mo, Nb, Ta, K, Na, V, Cr, Zr



FCC mřížka

Fe, Cu, Al, Au, Ag, Pb, Ni, Pt



HCP mřížka

Ti, Mg, Zn, Be, Co, Zr, Cd

Rozpor mezi teoretickou a reálně pozorovanou pevností

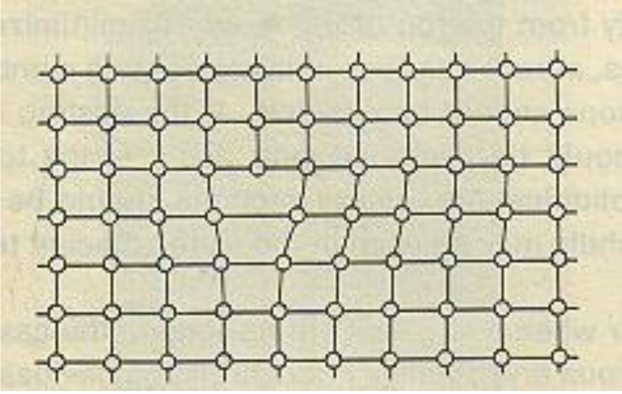
Fe: teoreticky spočítaná pro dokonalý krystal ~ 10 GPa

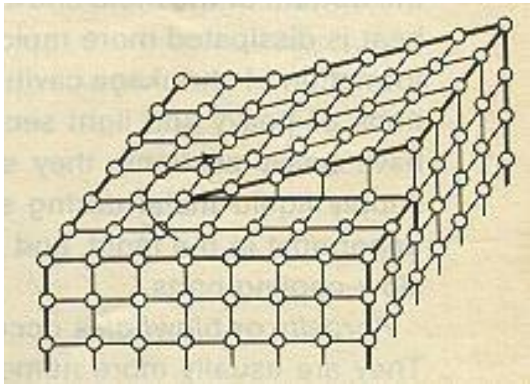
x

reálně pozorovaná pro čisté železo ~ 20 MPa

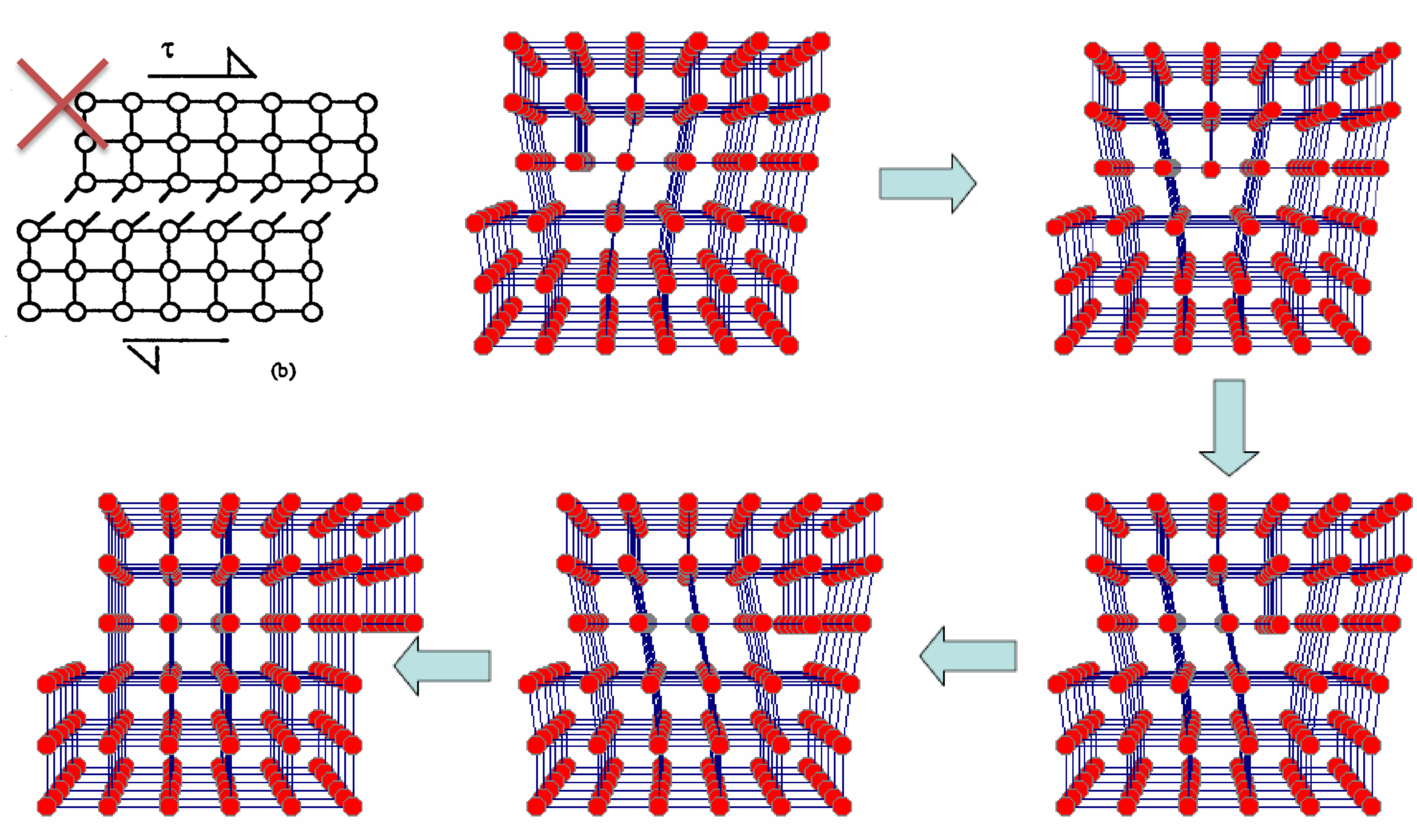
Poruchy krystalové mřížky

Dislokace





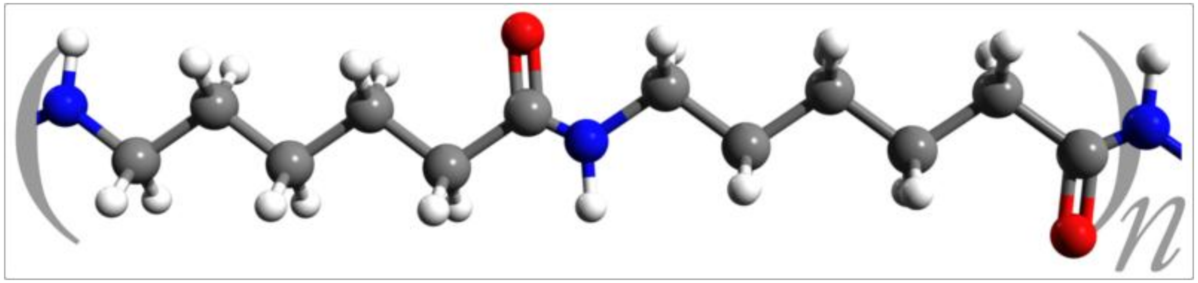
Pohyb dislokací



Polyamidy

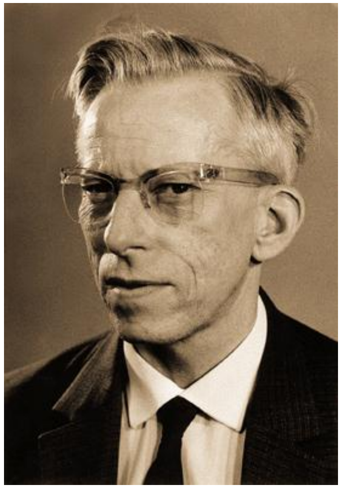
Nylon (1935) – první syntetické vlákno

mez pevnosti:
0,1 GPa
hustota:
1130 kg m^{-3}



Wallace Hume Carothers

Další: Silon, Perlon

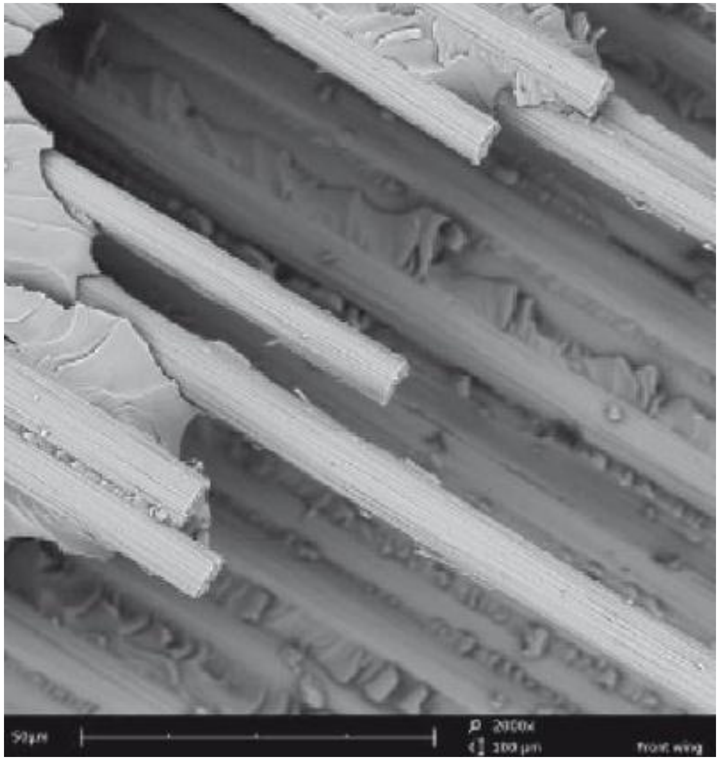


Uhlíkové vlákno

1879 – Edison
pro konstrukční využití známo cca 50 let

mez pevnosti:
3,5 – 7 GPa
hustota:
1750 kg m^{-3}

tloušťka 5 – 10 μm



Jak použít uhlíková vlákna v praktických výrobcích?

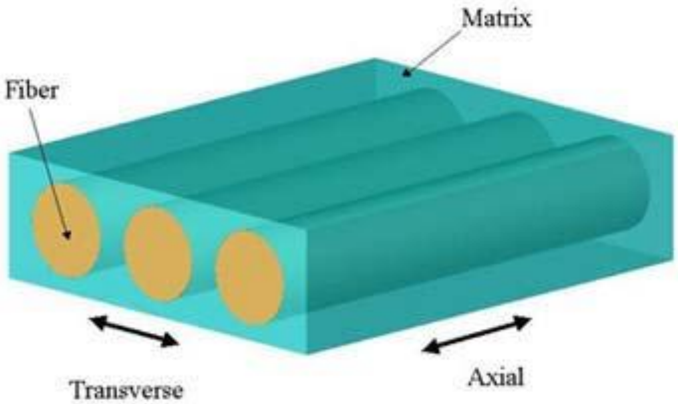
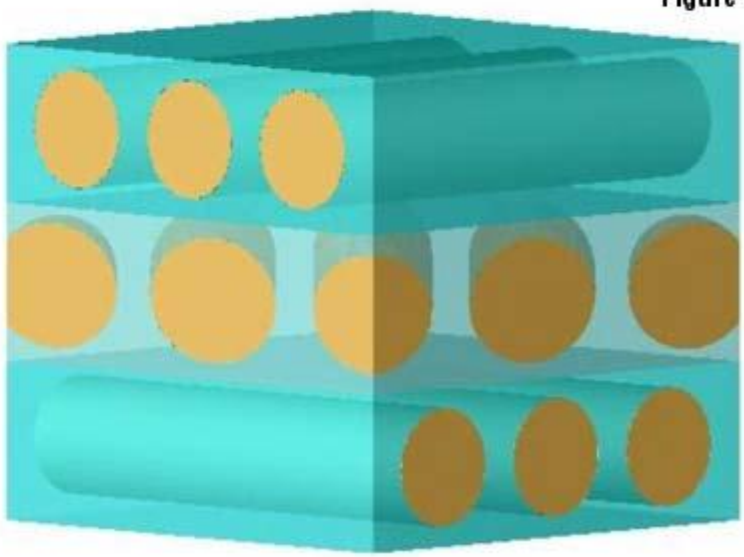


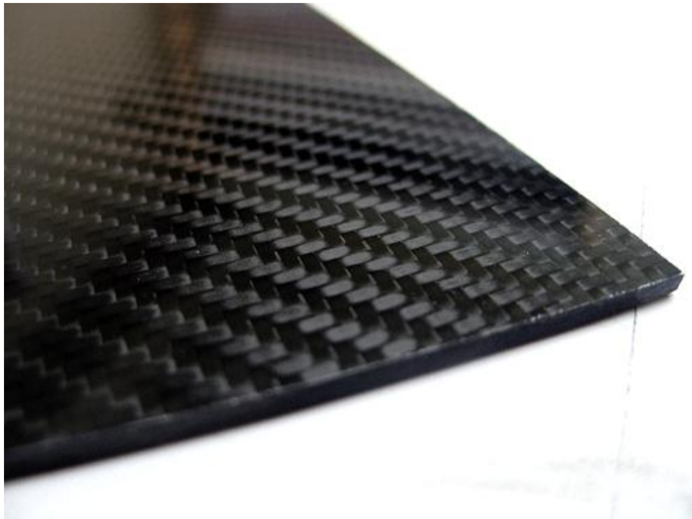
Figure 1 Lamina

Figure 6

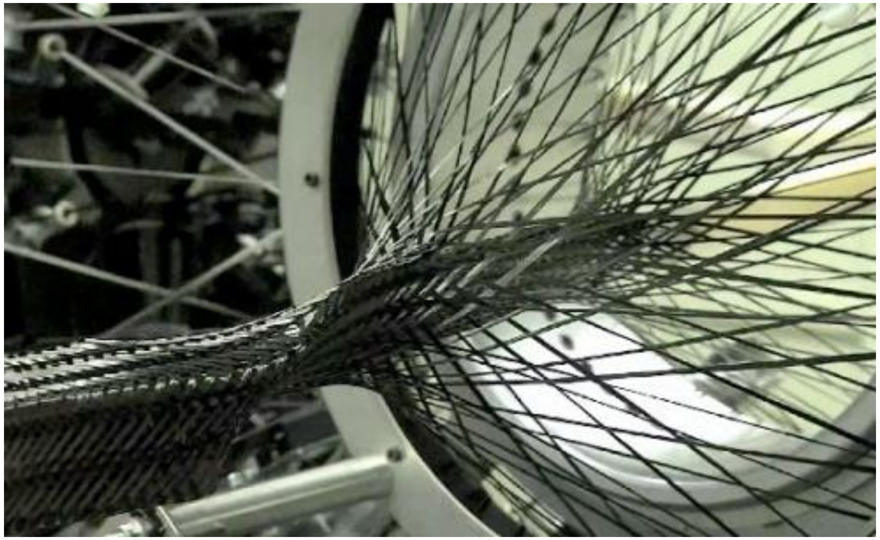


Laminate

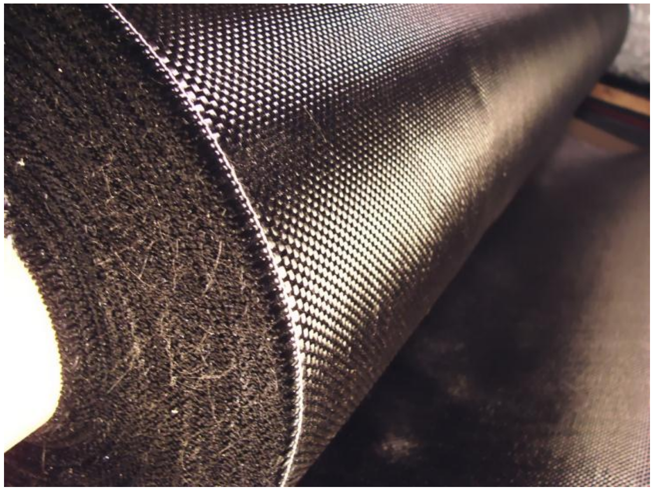
Hotové díly běžných tvarů

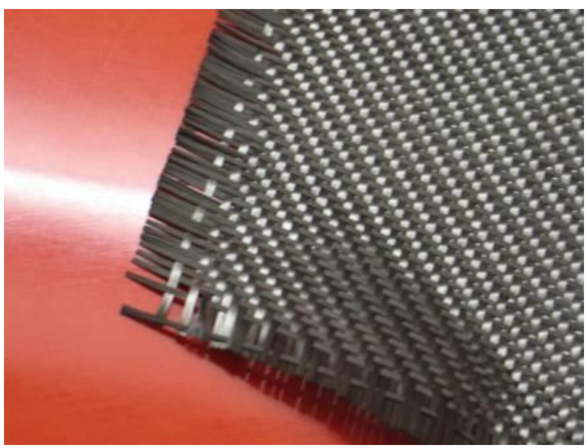


Výroba vidlice kola



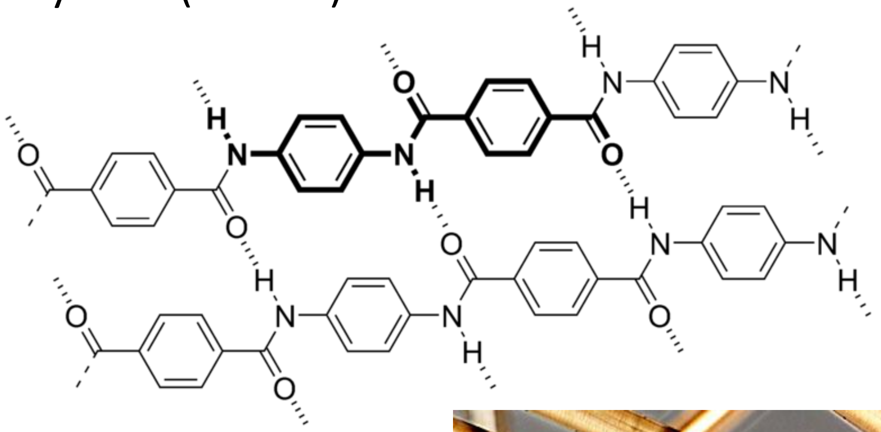
Výroba blatníku





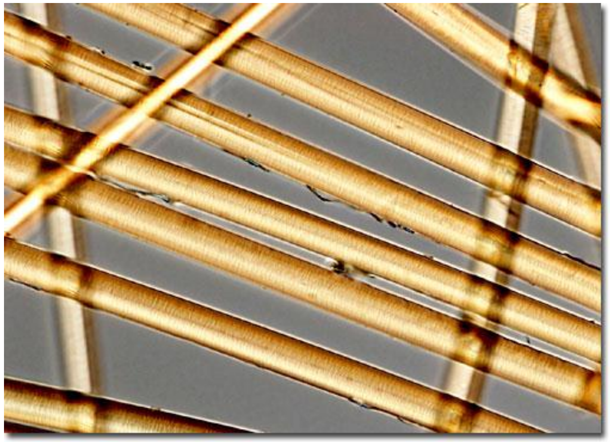
Aramidy

Kevlar (1965) – aromatický polyamid (aramid)



Stephanie Kwolek

mez pevnosti:
3,6 GPa
hustota:
1440 kg m^{-3}

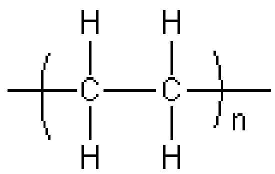


Polymery s aromatickými jádry a paralelně orientovanými řetězci v ose vlákna mají velmi vysokou pevnost a tuhost.

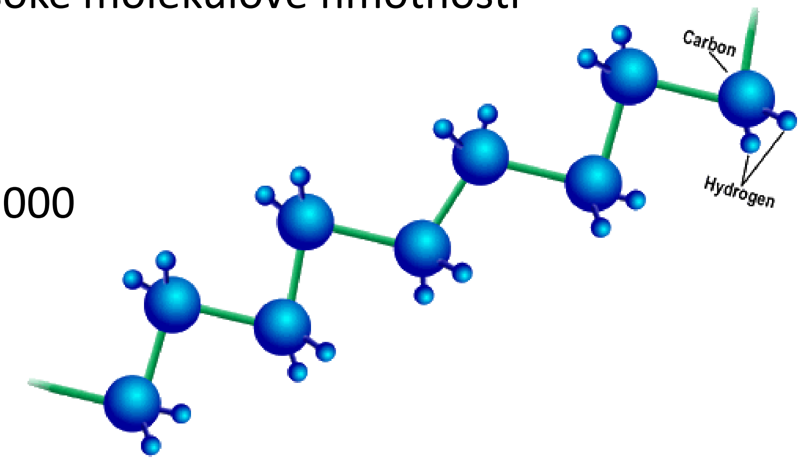
Další: Twaron

Polyetylény

Spectra (1979) – polyethylen o ultravysoké molekulové hmotnosti



n > 100 000



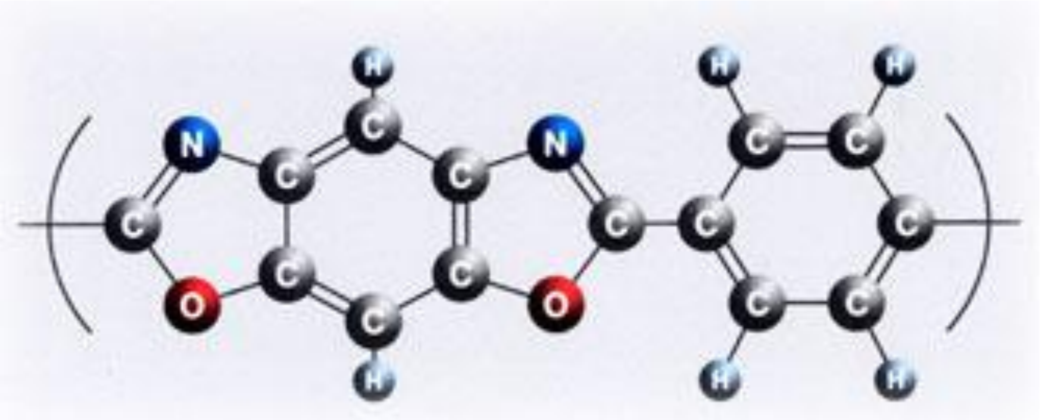
mez pevnosti: 3,5 GPa
hustota: 970 kg m^{-3}

Další: Dyneema

PBO – Polybenzazol

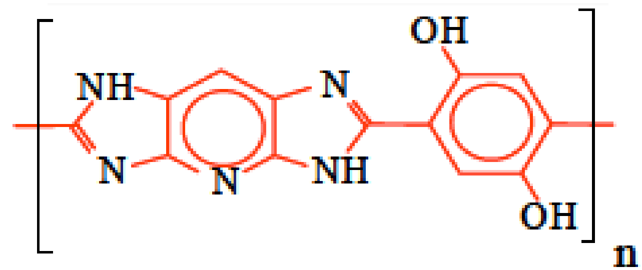
Zylon (80. léta 20 st.) – poly(p-fenylen-benzobisoxazol)

mez pevnosti:
5,8 GPa
hustota:
1550 kg m^{-3}

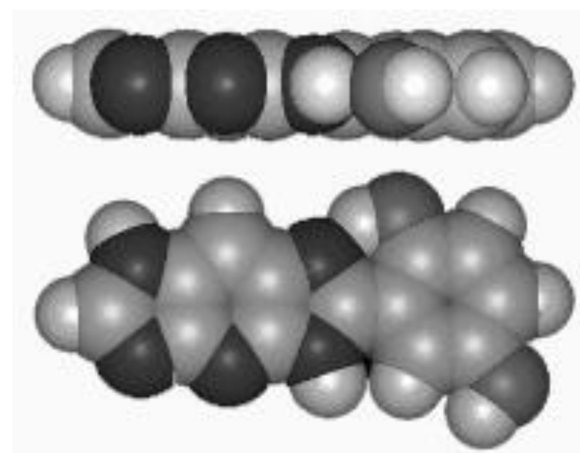


PIPD

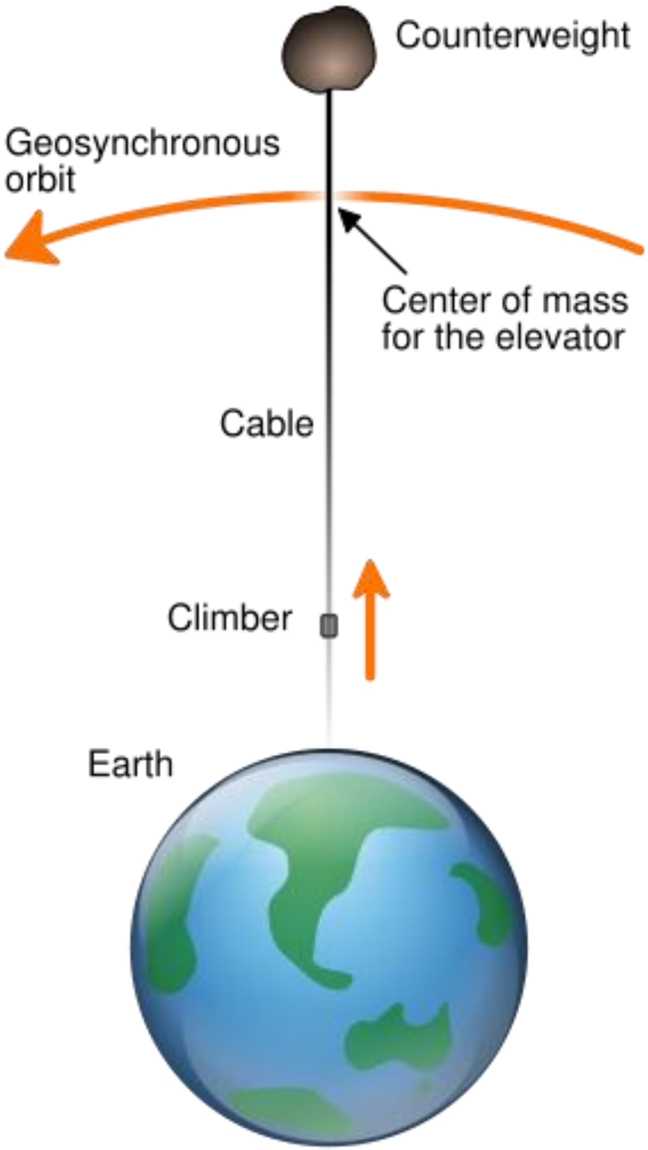
M5 (1999) – poly{2,6-diimidazo[4,5-b:4',5'-E]pyridinylen-1,4-(2,5-dihydroxy)fenylen}



mez pevnosti:
5,7 GPa (výhledově 9,5 GPa)
hustota:
1700 kg m^{-3}



Vesmírný výtah



Požadavky na materiál nosného lana

$$\boxed{\frac{\text{Průřez (země)}}{\text{Průřez (geost.)}} = e^{-4{,}86\cdot 10^{7}\,\mathrm{m^2 s^{-1}}\,\frac{\text{hustota}}{\text{pevnost}}}}$$

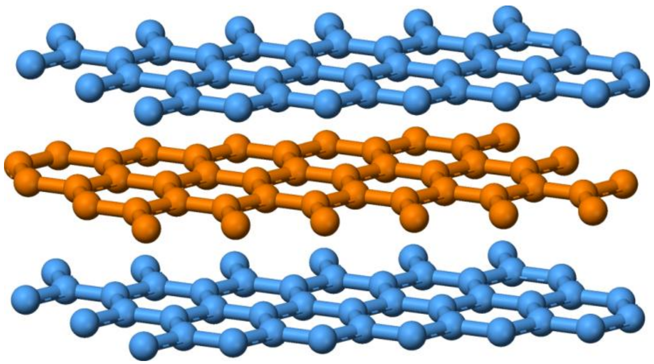
Jaký by byl poměr zúžení pro běžně dostupné materiály?

Ocel: 1.7×10^{33}

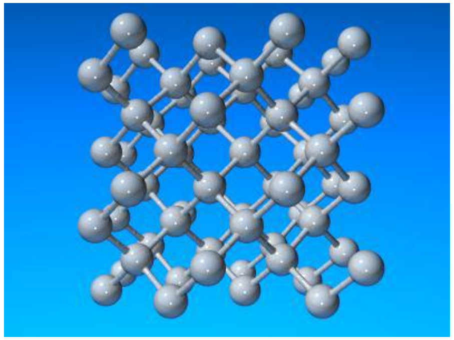
Kevlar: 2.6×10^{8}

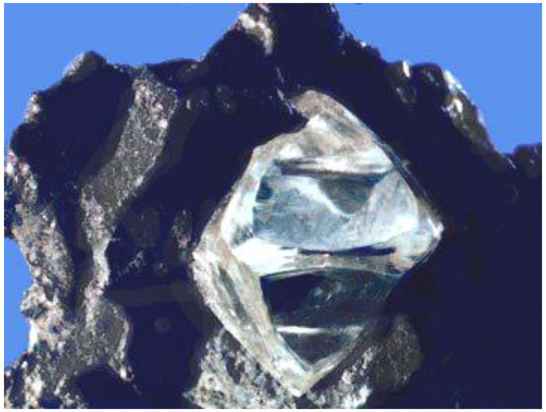
Modifikace uhlíku

grafit

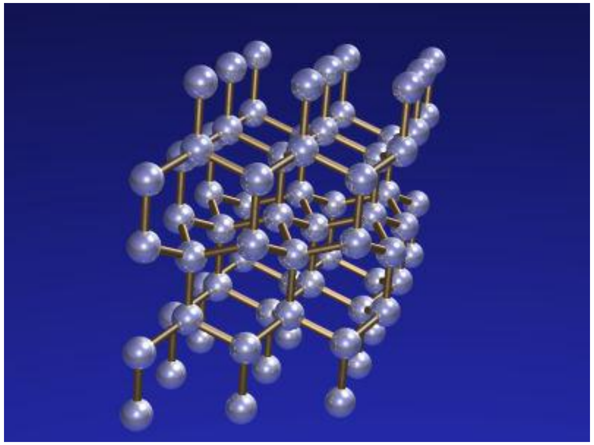


diamant





lonsdaleite



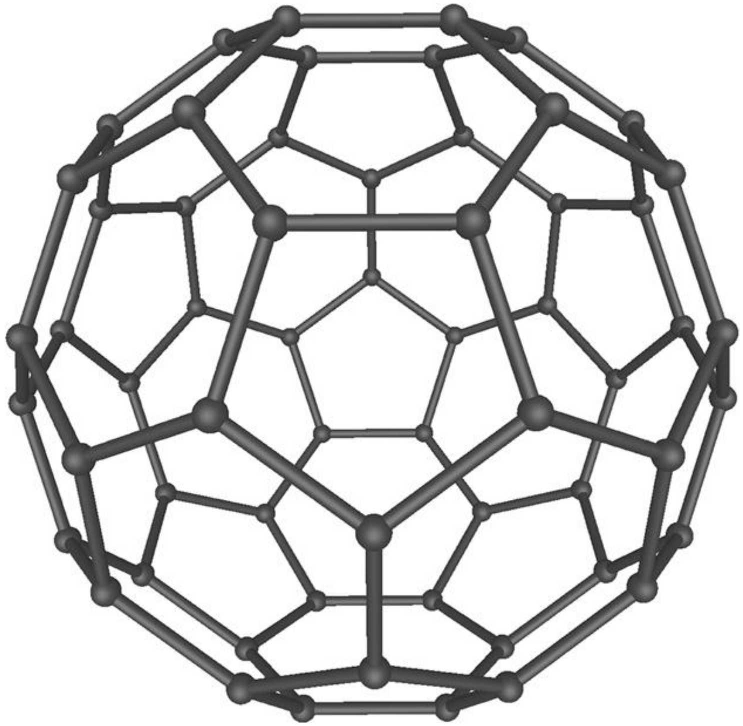
a ...

Fullereny

Kroto, Curl, Smalley

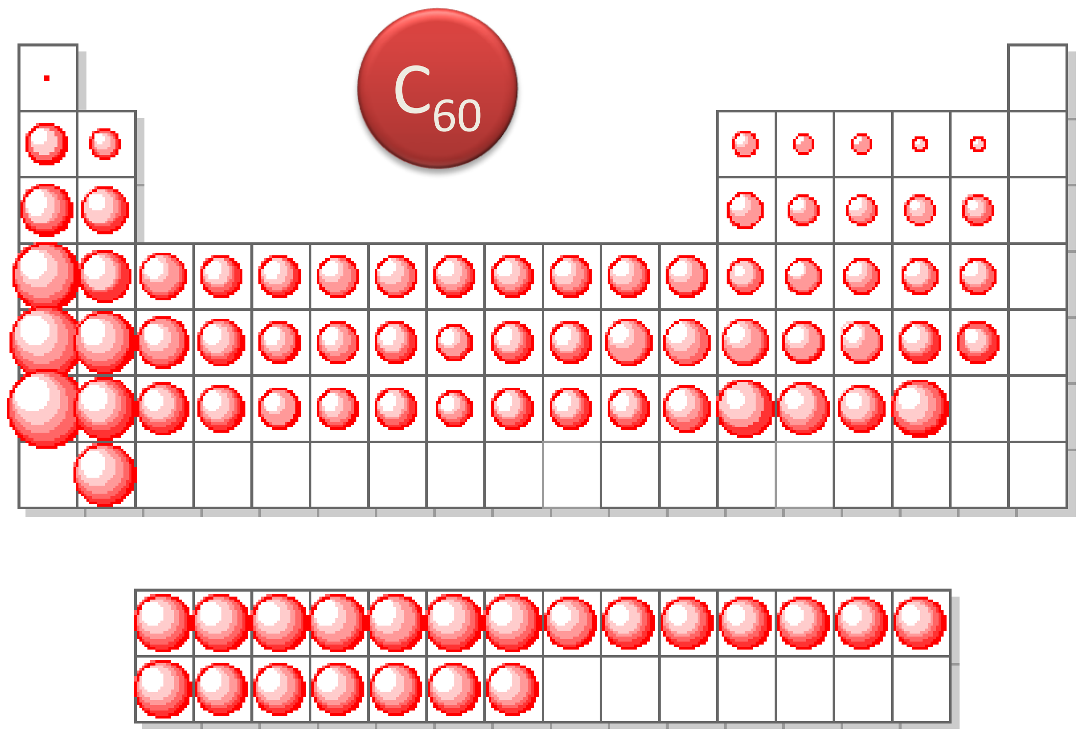
1985 – prvotní objev

1996 – Nobelova cena

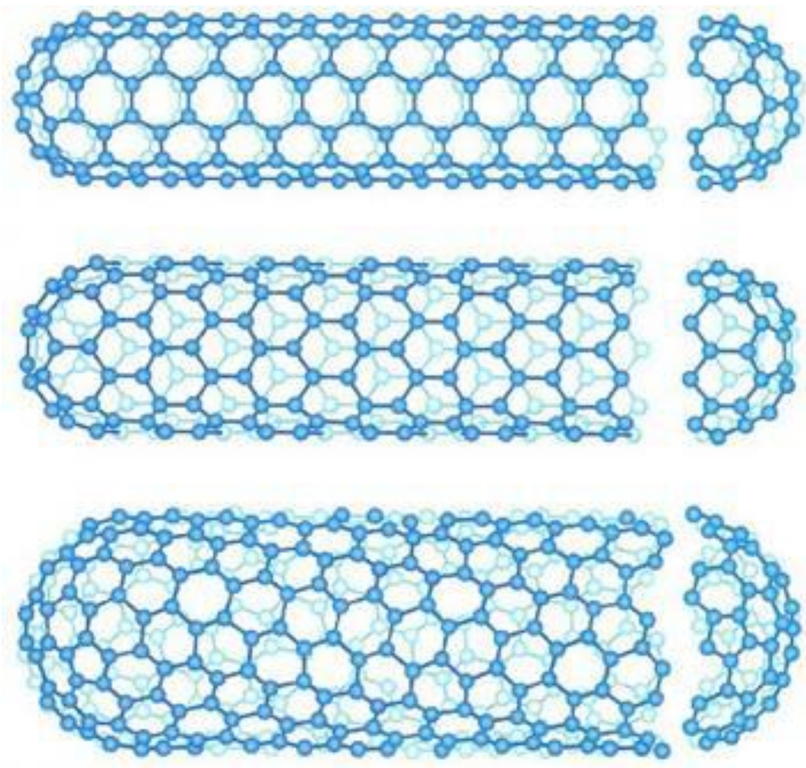


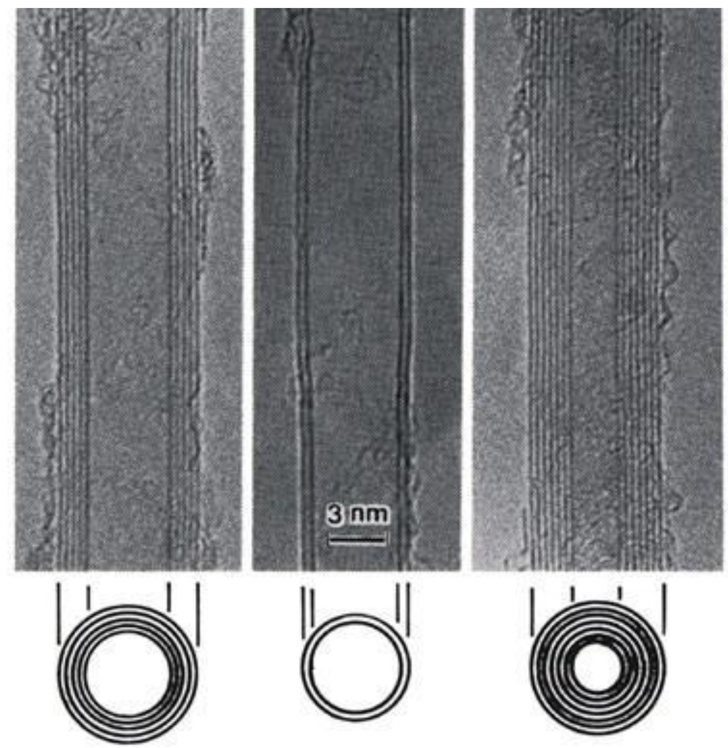
Velikost molekuly fullerenu

D_{C60}=10.18Å
D_{Fe}=2.52Å
D_{Co}=2.50Å
D_{Ni}=2.50Å
D_{C}=1.54Å



Uhlíkové nanotrubičky



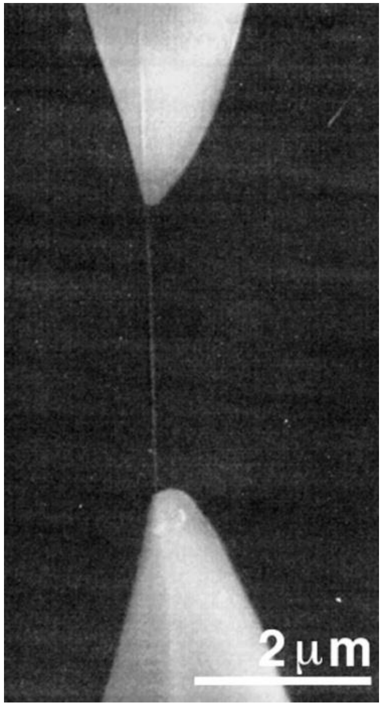


Uhlíkové nanotrubičky – pevnost

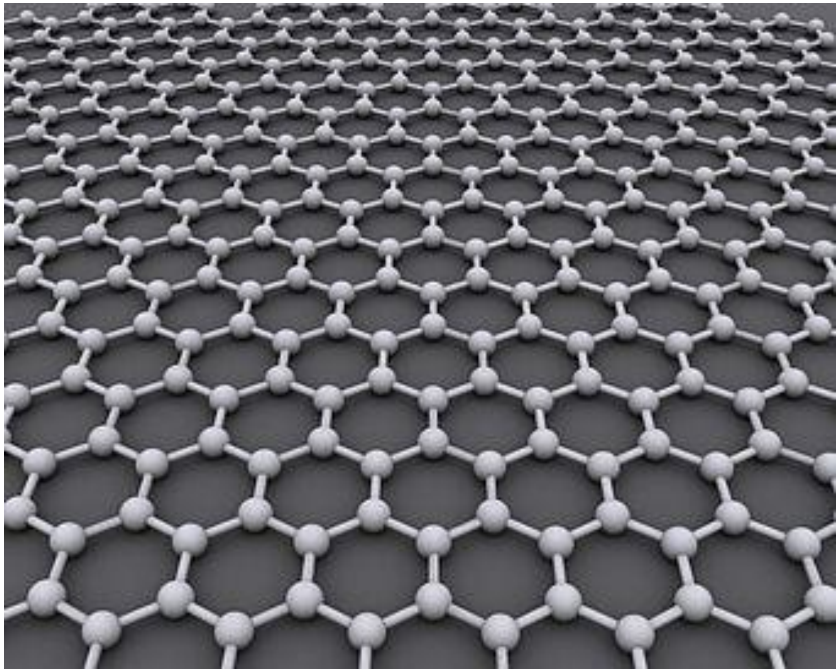
prvně vyrobeny v r. 1991

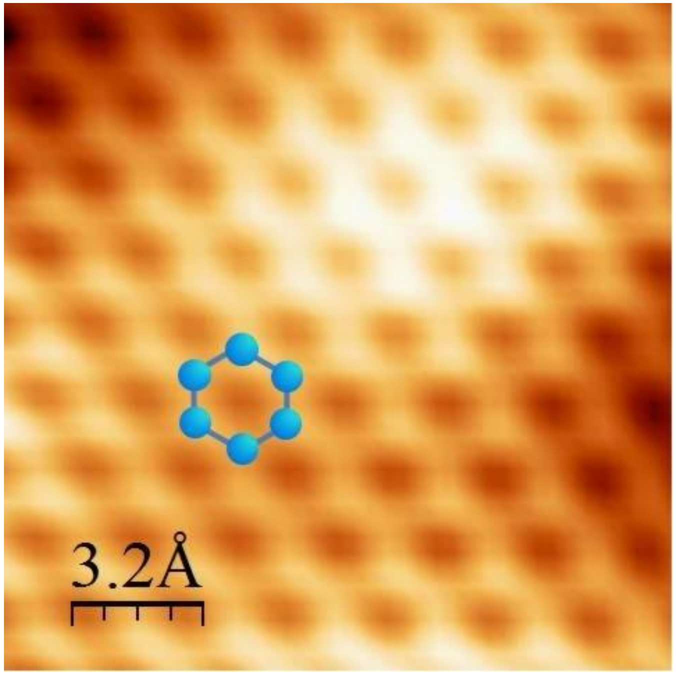
pevnost v tahu: ~65 GPa (teoreticky 130 GPa, podle některých zdrojů až 300 GPa)

hustota: 1300 kg m^{-3}

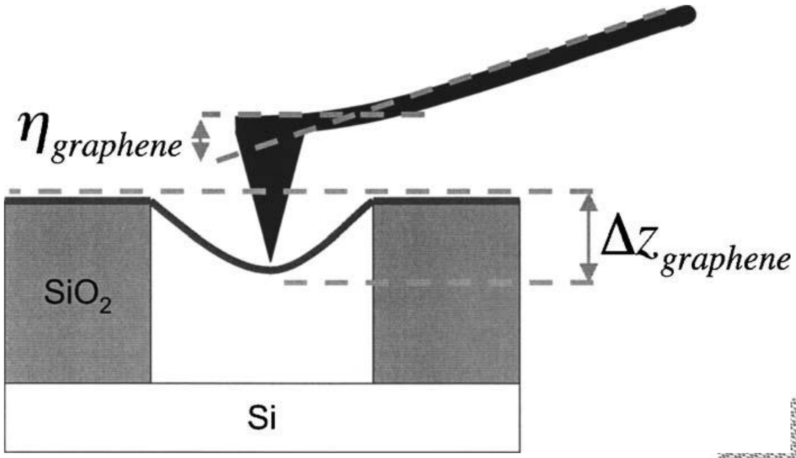


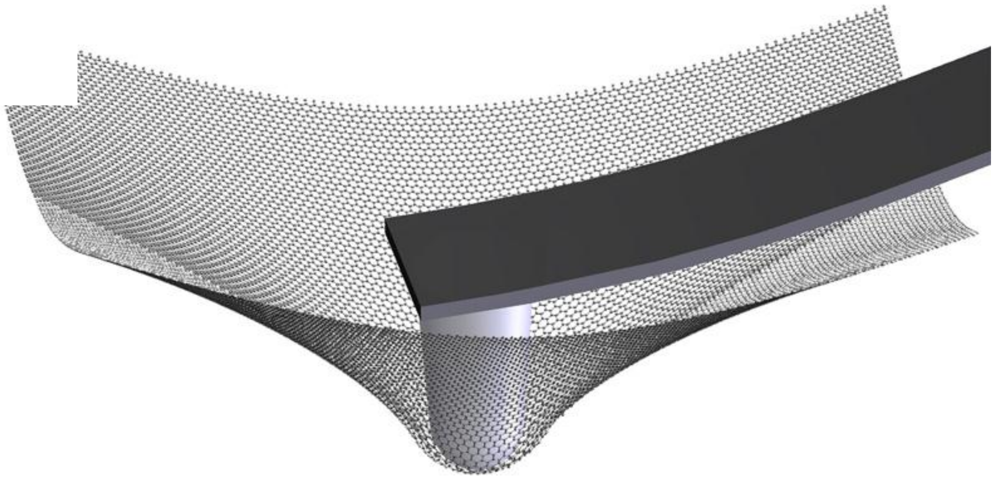
Grafen (2004)



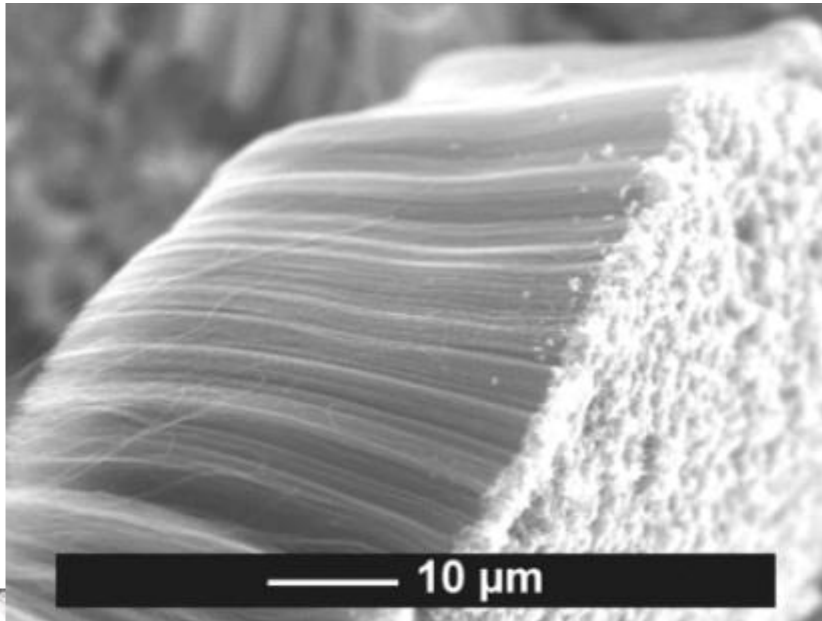


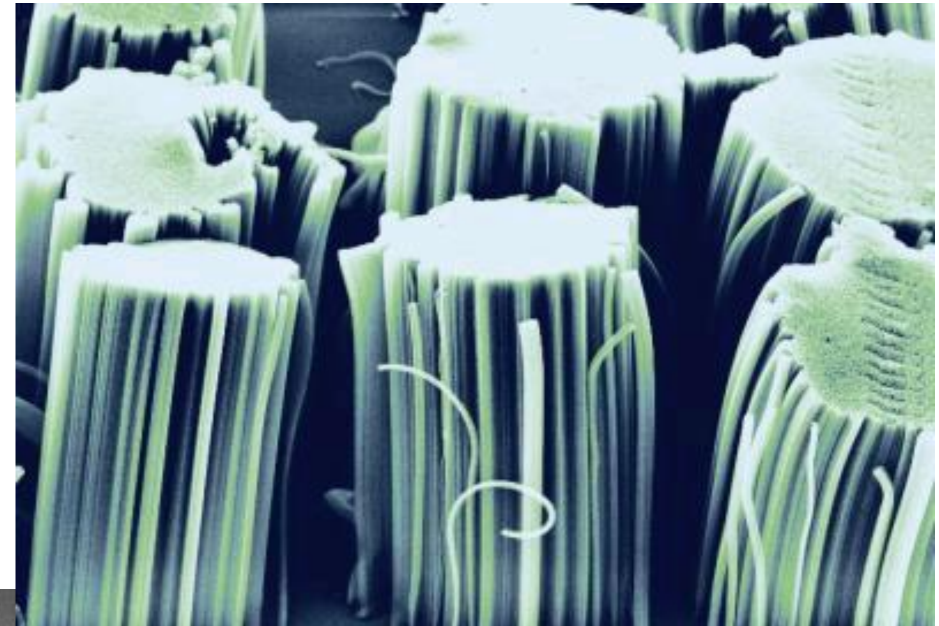
Grafen – měření tuhosti a pevnosti

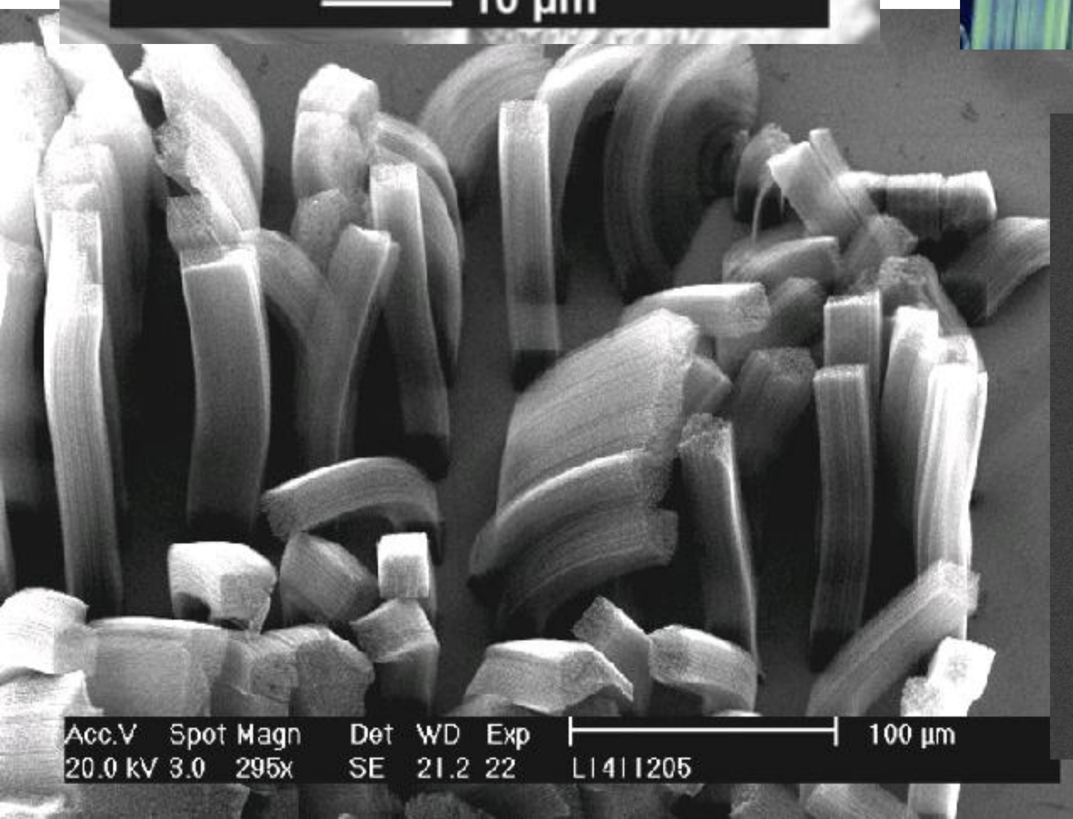


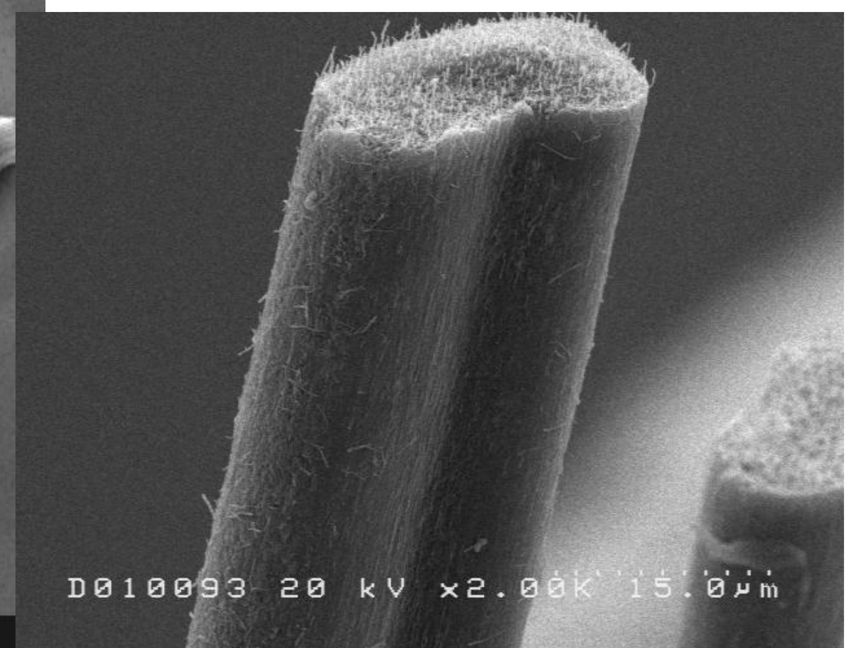


2008: potvrzena ideální pevnost (pevnost vazby) : 130 GPa


10 µm




Acc.V Spot Magn Det WD Exp
20.0 kV 3.0 295x SE 21.2 22
100 µm
L1411205

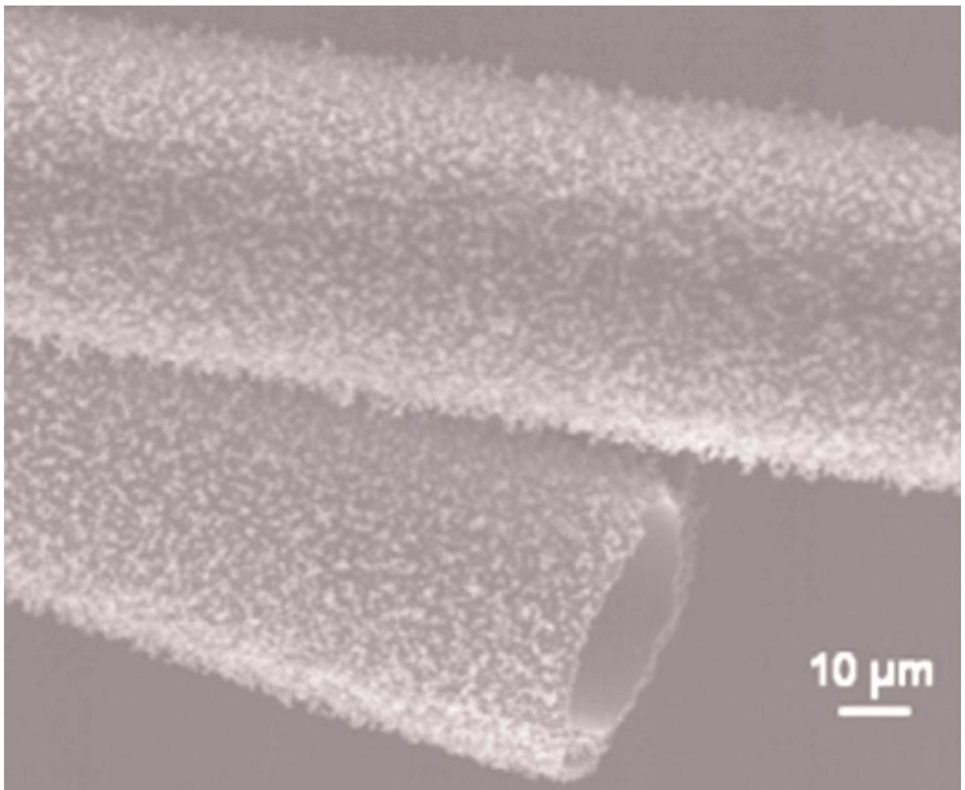

D010093 20 kV x2.00K 15.0µm

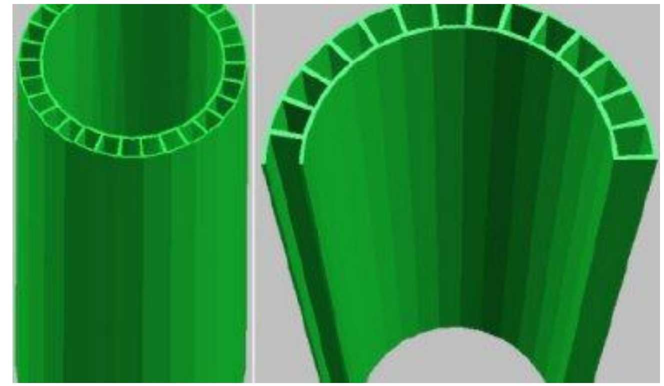
„Kolosální“ uhlíková trubička

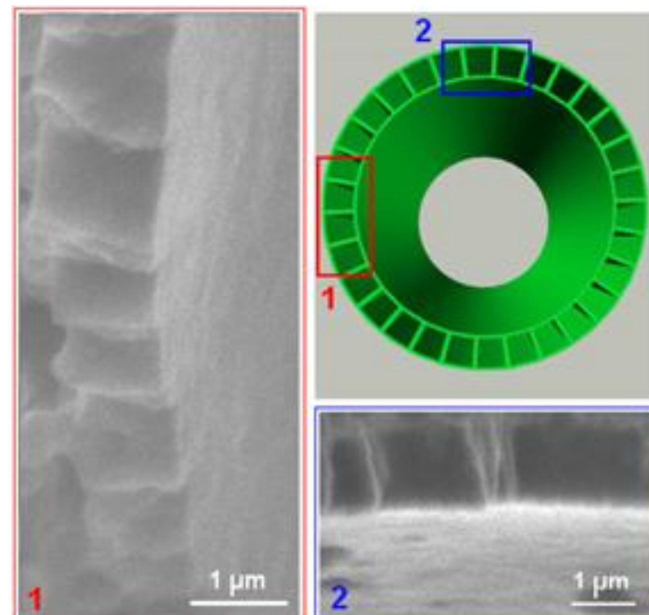
Publikováno 2008

pevnost v tahu: 6,9 GPa

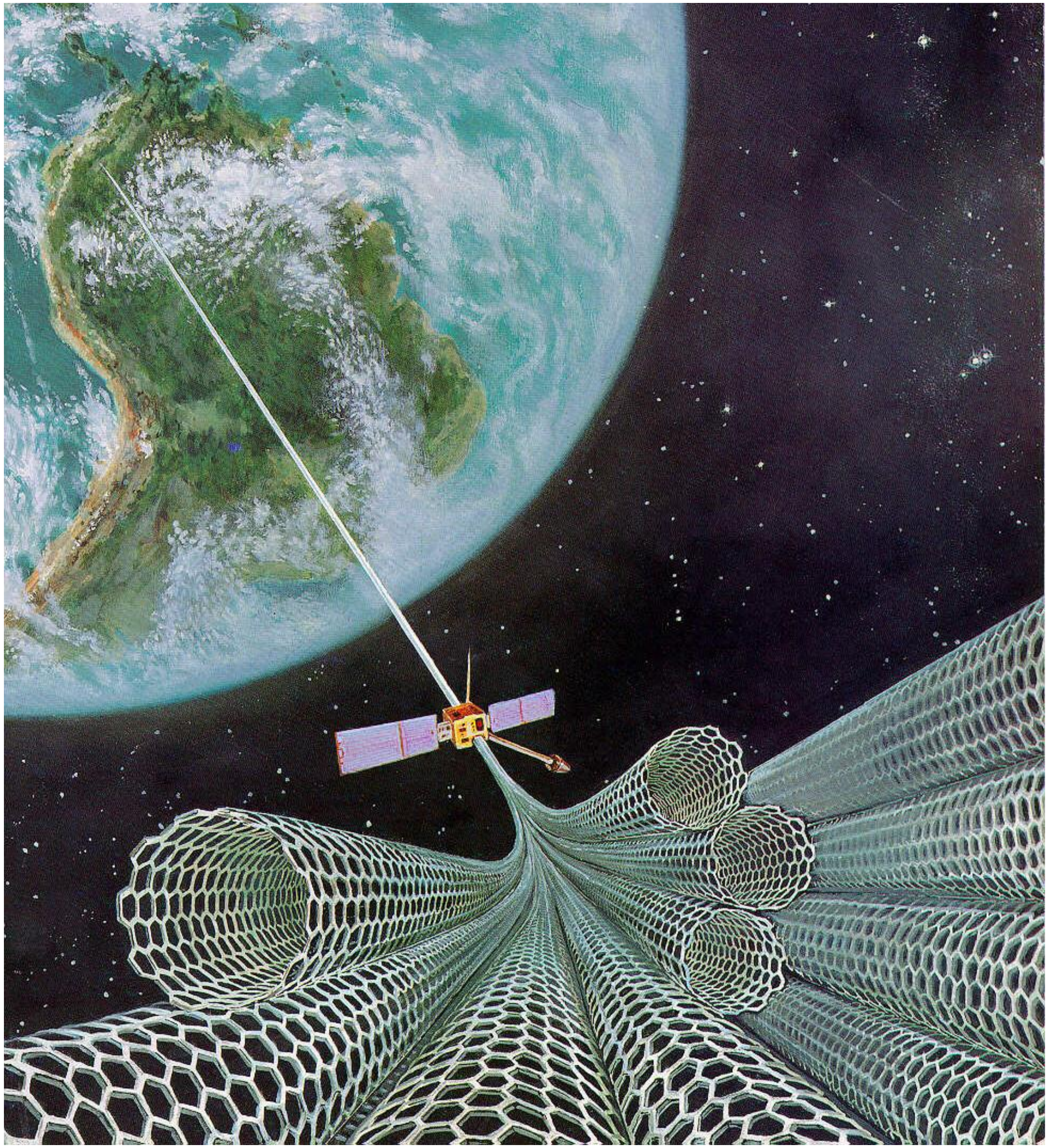
hustota: 116 kg m^{-3} !!!





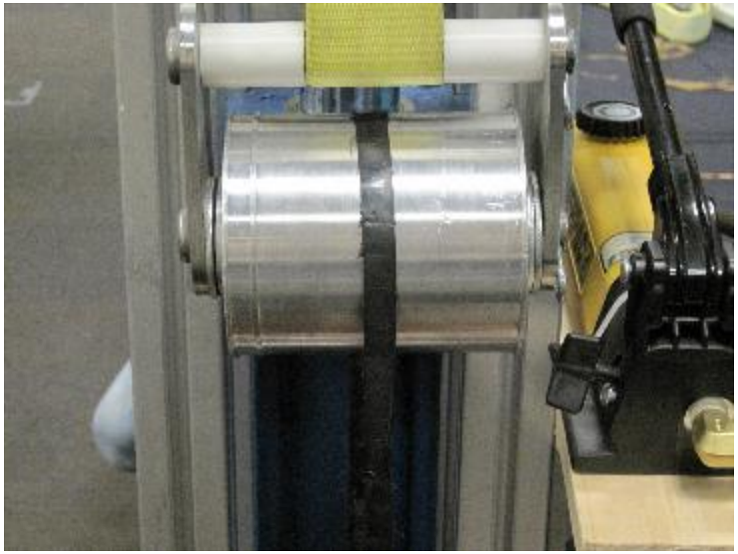


Material	Strength (MPa)	Density (g/cm³)	Specific Strength (kN·m/kg)	Breaking length (km)
Scifer steel wire	5500	7.87	706	71.2
Bainite	2500	7.87	321	32.4
1 µm iron whiskers	14000	7.87	1800	183
Concrete	10	2.3	4.35	0.44
Rubber	15	0.92	16.3	1.66
Brass	580	8.55	67.8	6.91
Oak	60	0.69	86.95	8.86
Balsa (axial load)	73	0.14	521	53.2
Polypropylene	80	0.9	88.88	9.06
Nylon	78	1.13	69	7.04
Magnesium	275	1.74	158	16.11
Aluminium (alloy)	600	2.7	222	22.65
Steel	2000	7.86	254	25.93
Titanium (alloy)	1300	4.51	288	29.38
carbon-epoxy composite	1240	1.58	785	80
Silicon carbide	3440	3.16	1088	110
Glass fiber	3400	2.6	1307	133
Vectran	2900	1.4	2071	211
Carbon fiber (AS4)	4300	1.75	2457	250
Kevlar	3620	1.44	2514	256
Spectra fiber	3510	0.97	3619	369
Colossal carbon tube	6900	0.116	59483	6066
Carbon nanotube	62000	0.037-1.34	46268	4716



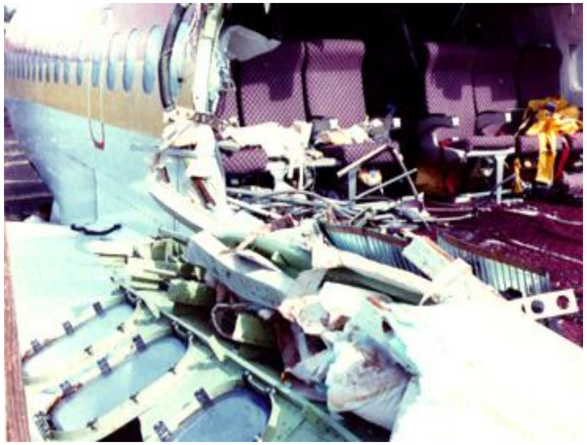
The 2009 Tether Competition

By the numbers:
Tether Length: **2 m** (closed loop)
Tether Weight: **2 g**
Breaking Force: **1 ton, 1.5 ton** (approx)
Prize Purse: **$900k, $1.1M**
Best performance to date: **0.72 Ton**



CO SNIŽUJE PEVNOST KONSTRUKCÍ?

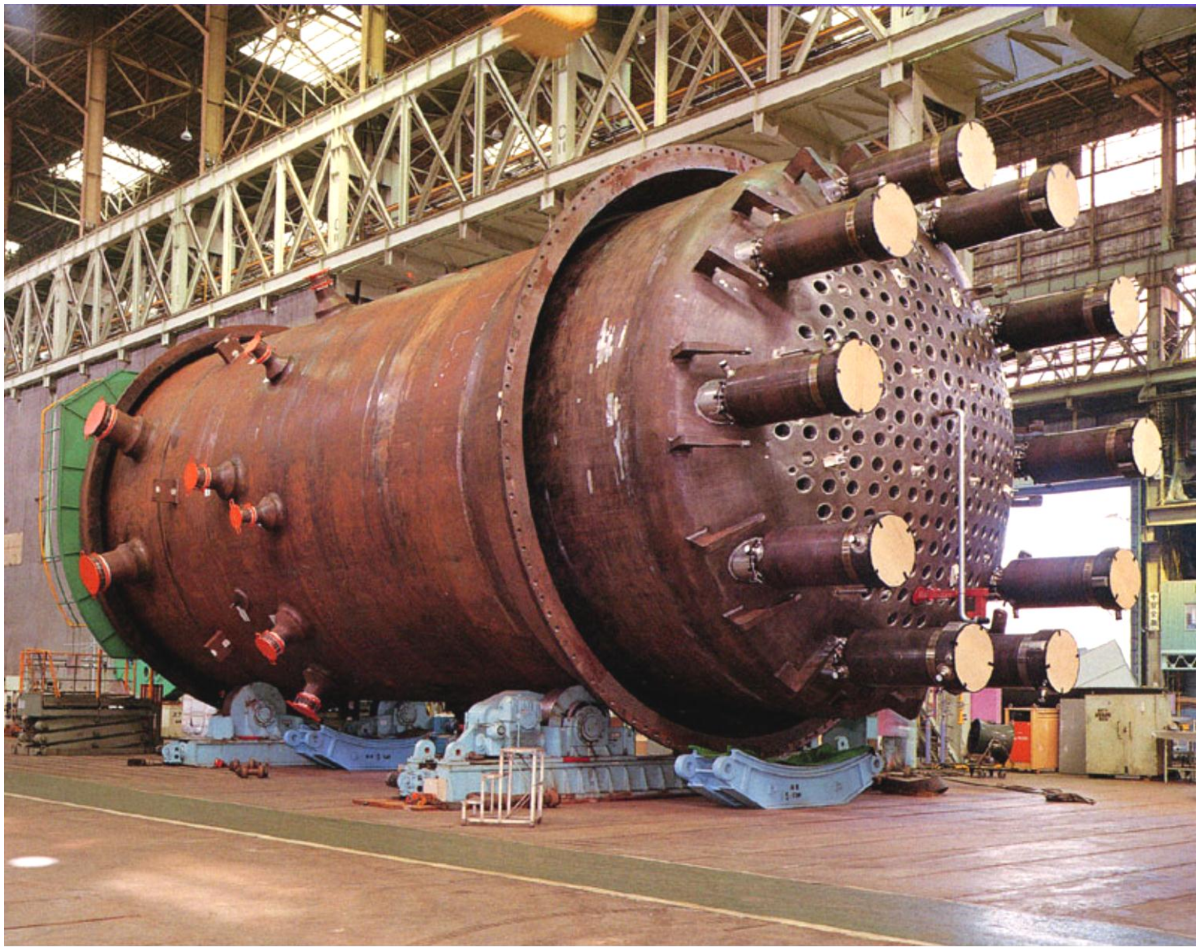
Únava materiálů



Havárie letadla Boeing 737, Hawaii, 1988

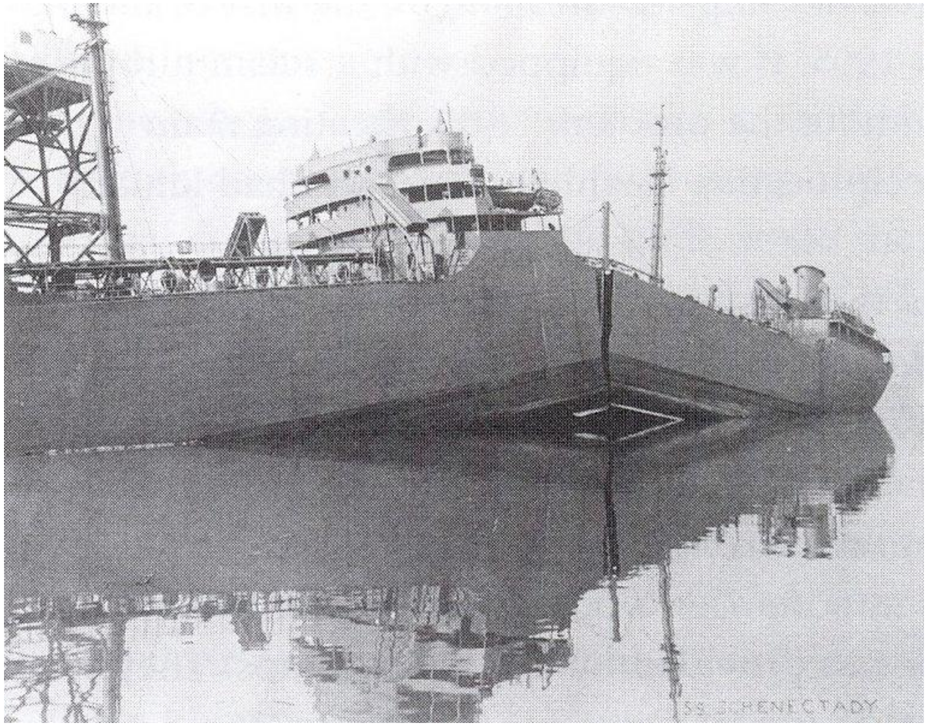
Únavová zkouška draku letadla

Radiační poškození

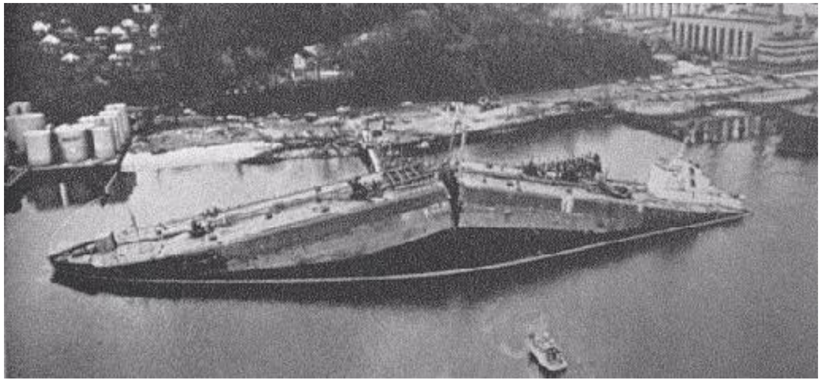


Tlaková nádoba jaderného reaktoru

Křehký lom

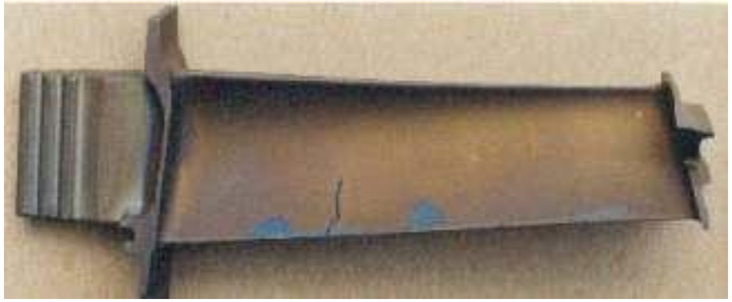


1943, tanker *Liberty*

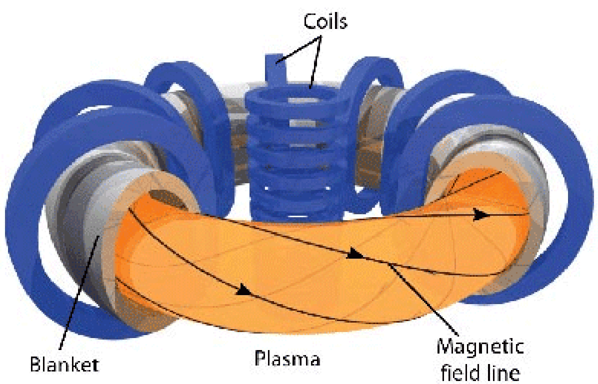


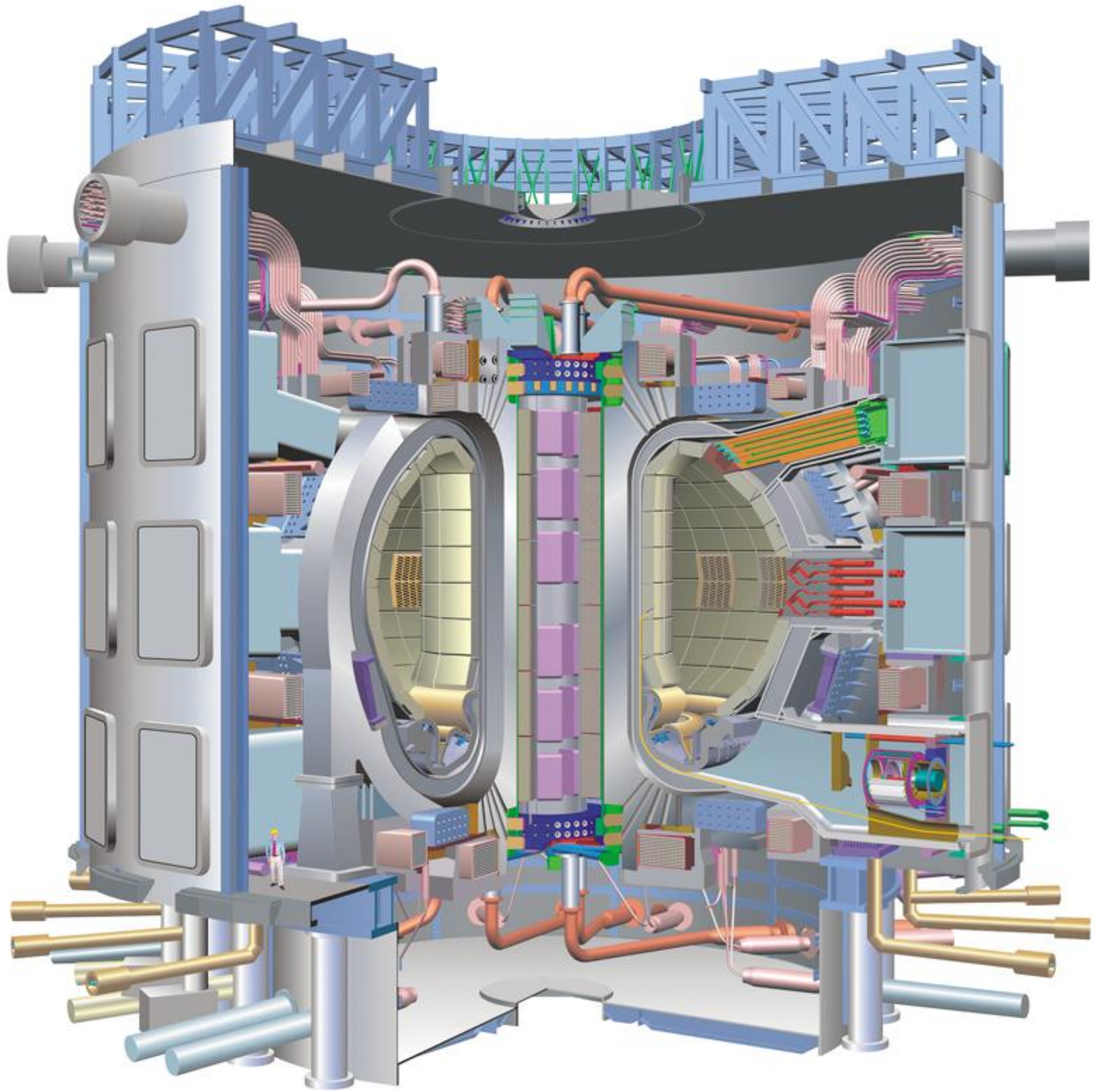
Tečení materiálu

parní turbína

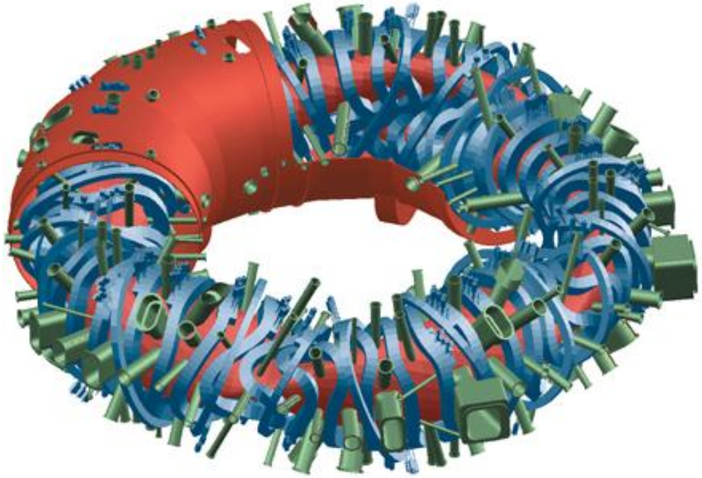


Tokamak
ITER

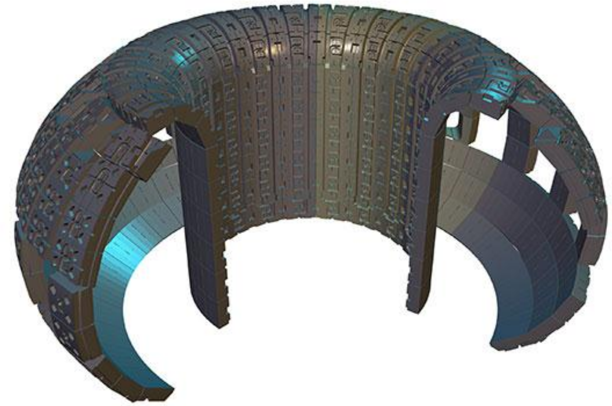


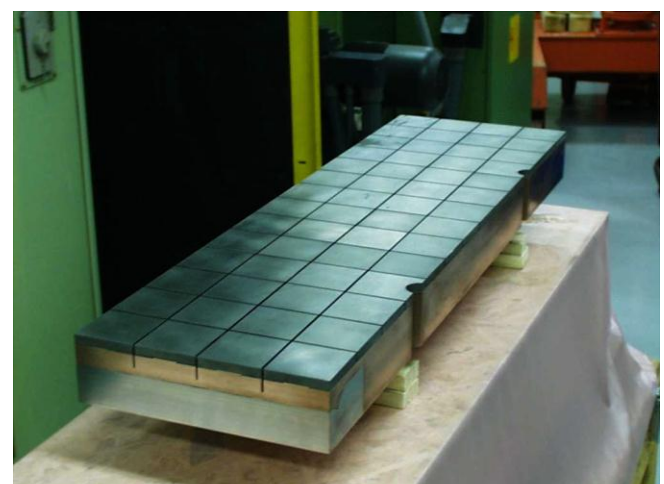


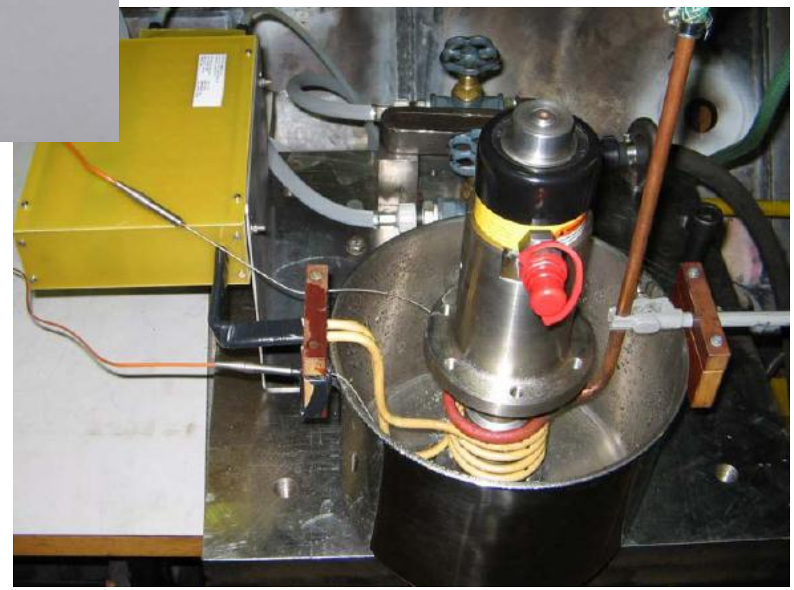
Stelarátor Wendelstein 7-X

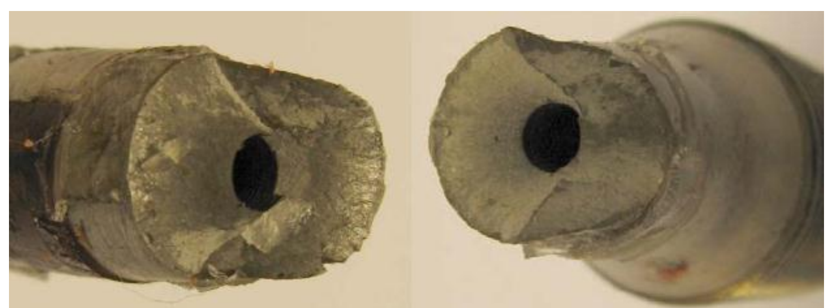


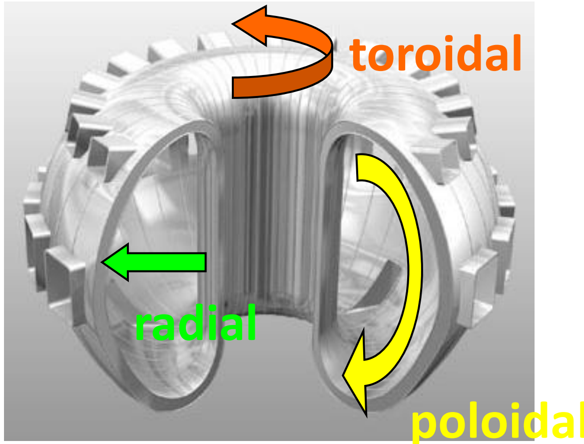
Panely na vnitřní straně reaktoru

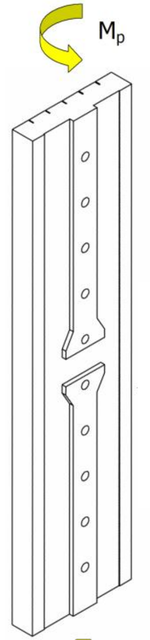


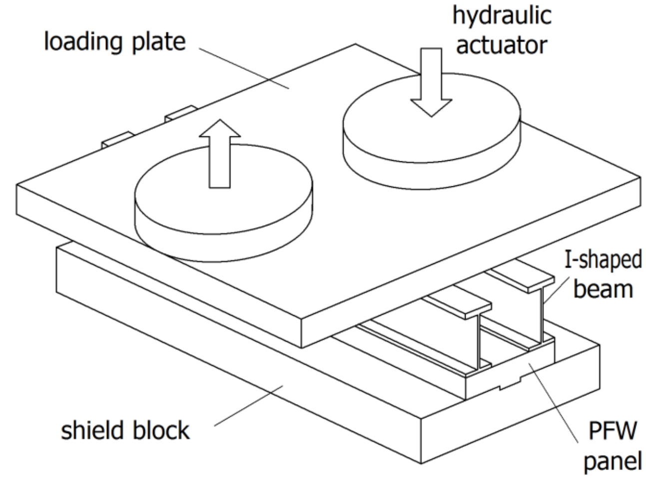


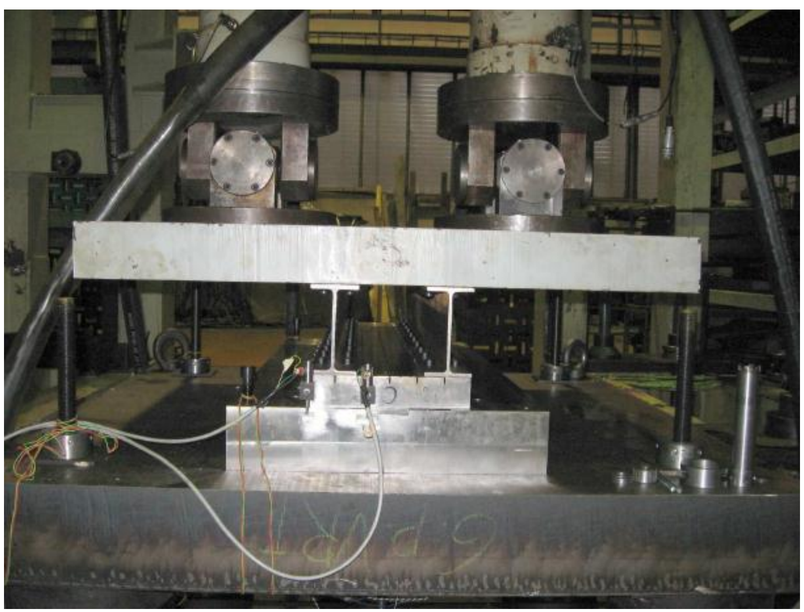




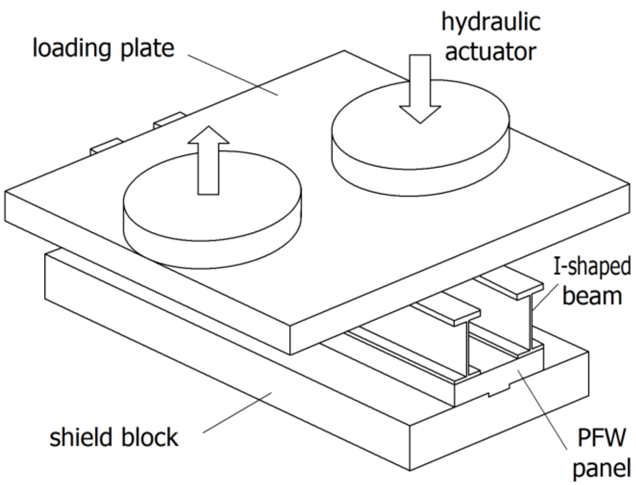

toroidal
radial
poloidal

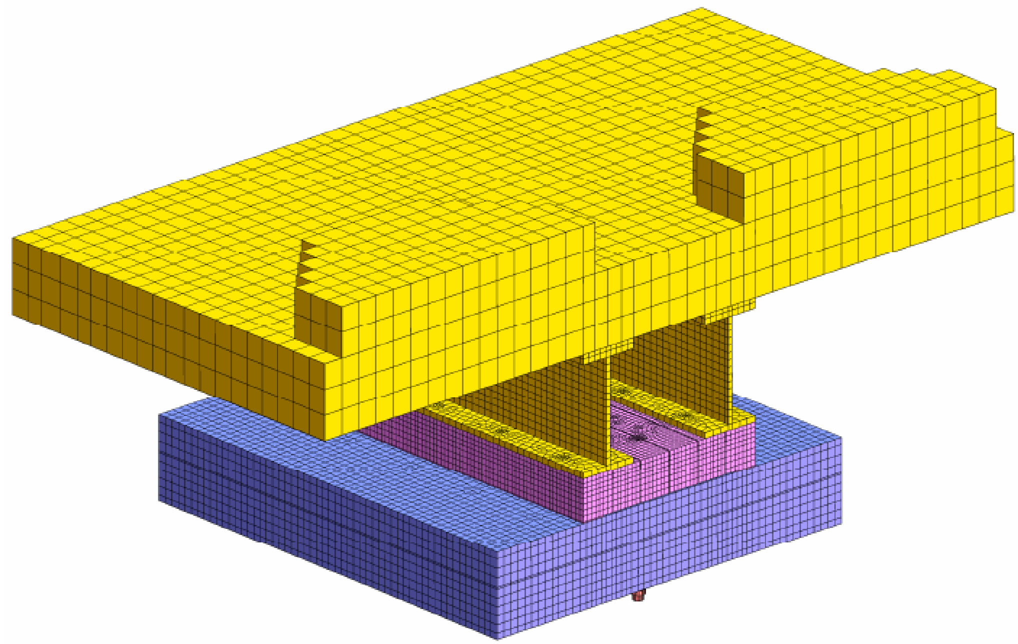

M_p

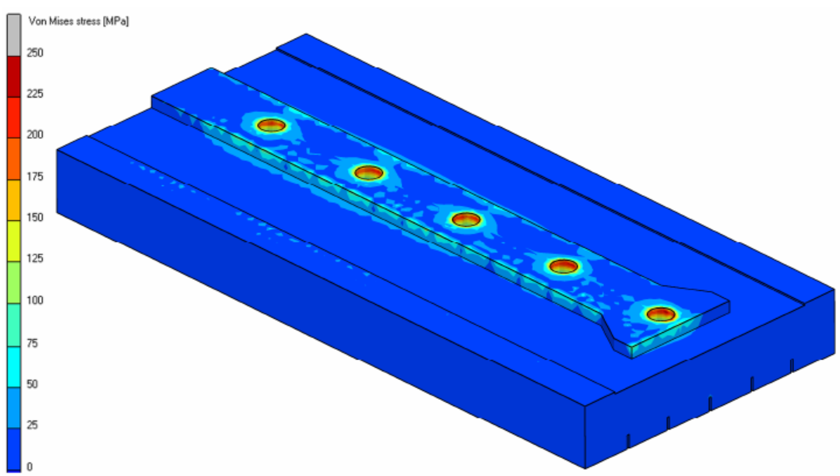

loading plate
hydraulic actuator
I-shaped beam
shield block
PFW panel

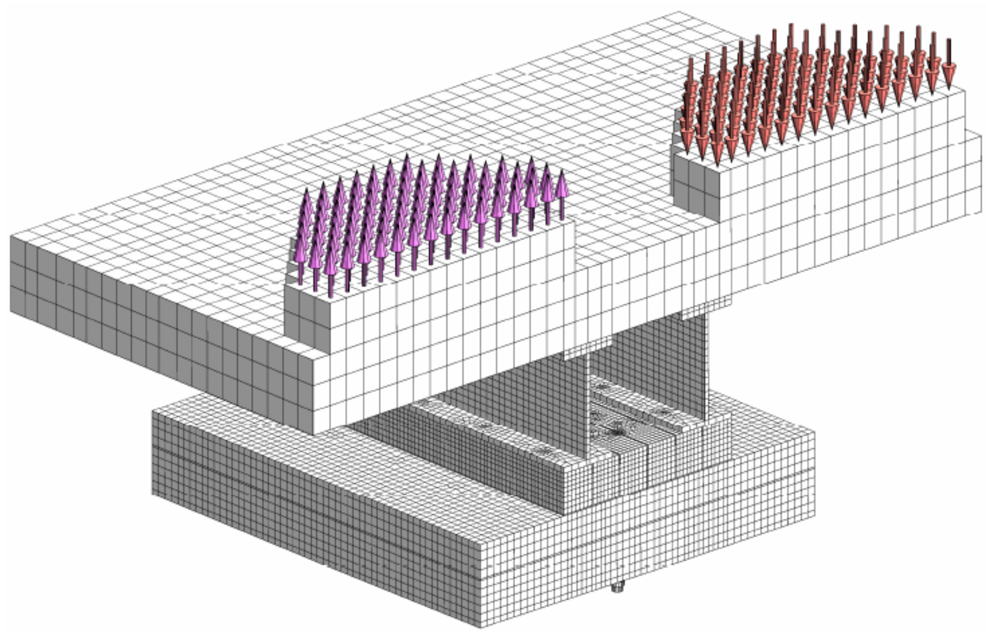



SCHENCK

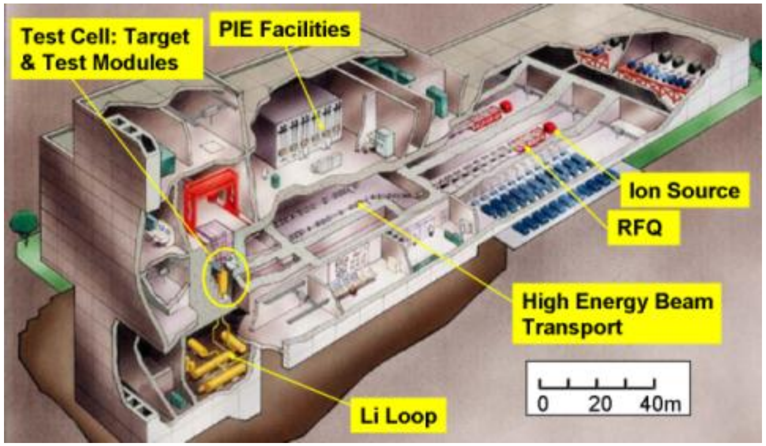

hydraulic
actuator
loading plate
I-shaped
beam
shield block
PFW
panel




Von Mises stress [MPa]
250
225
200
175
150
125
100
75
50
25
0

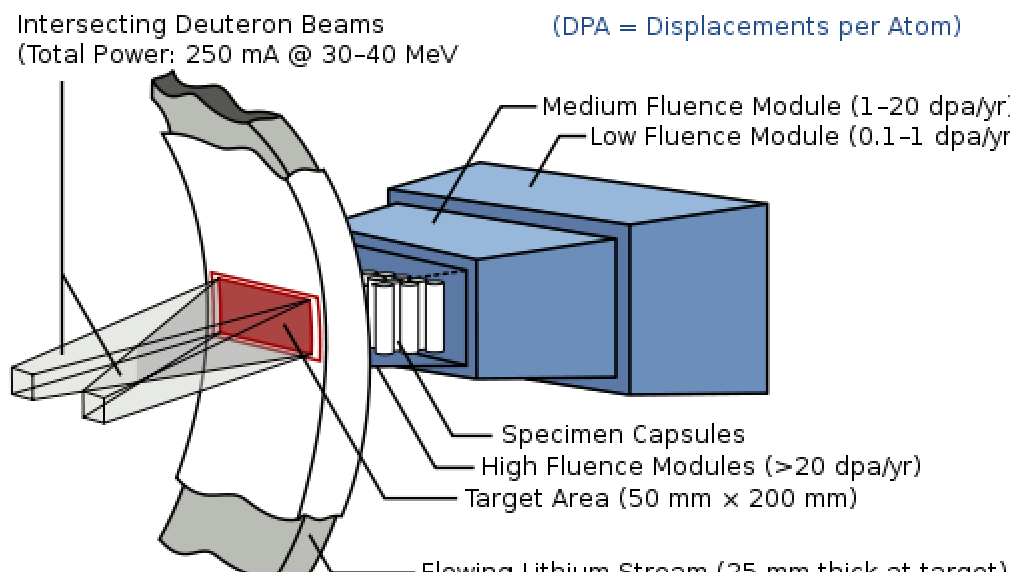


IFMIF – International Fusion Materials Irradiation Facility



Rokkasho (Japonsko)

(DPA = Displacements per Atom)



Materials are the stuff of which our world is made.