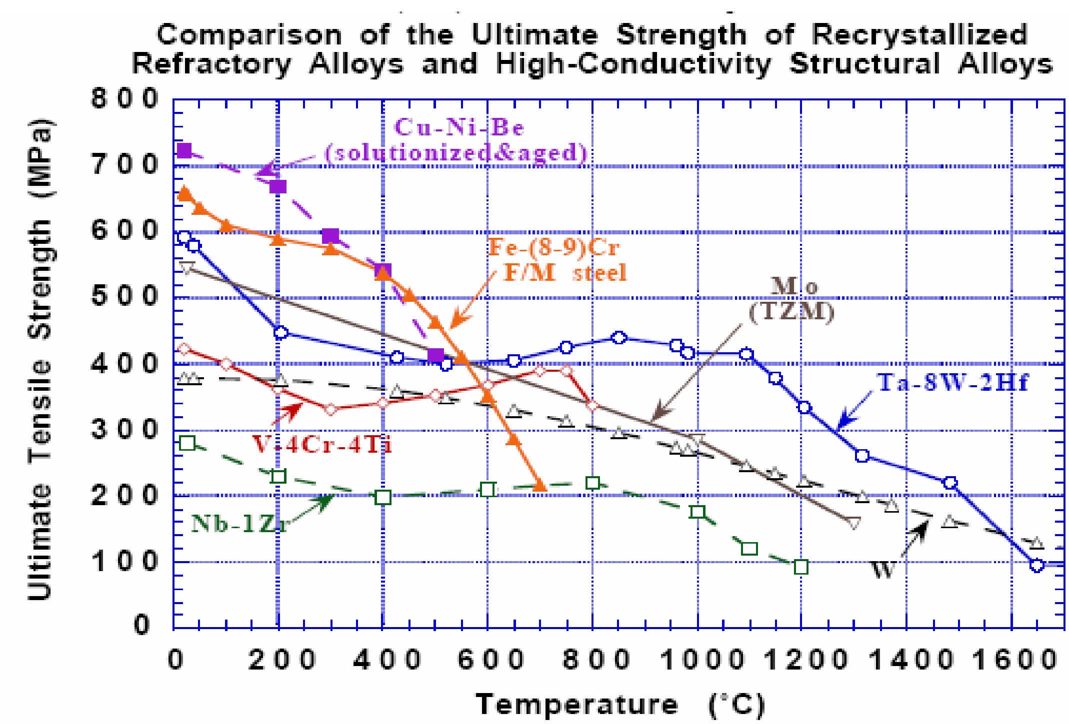
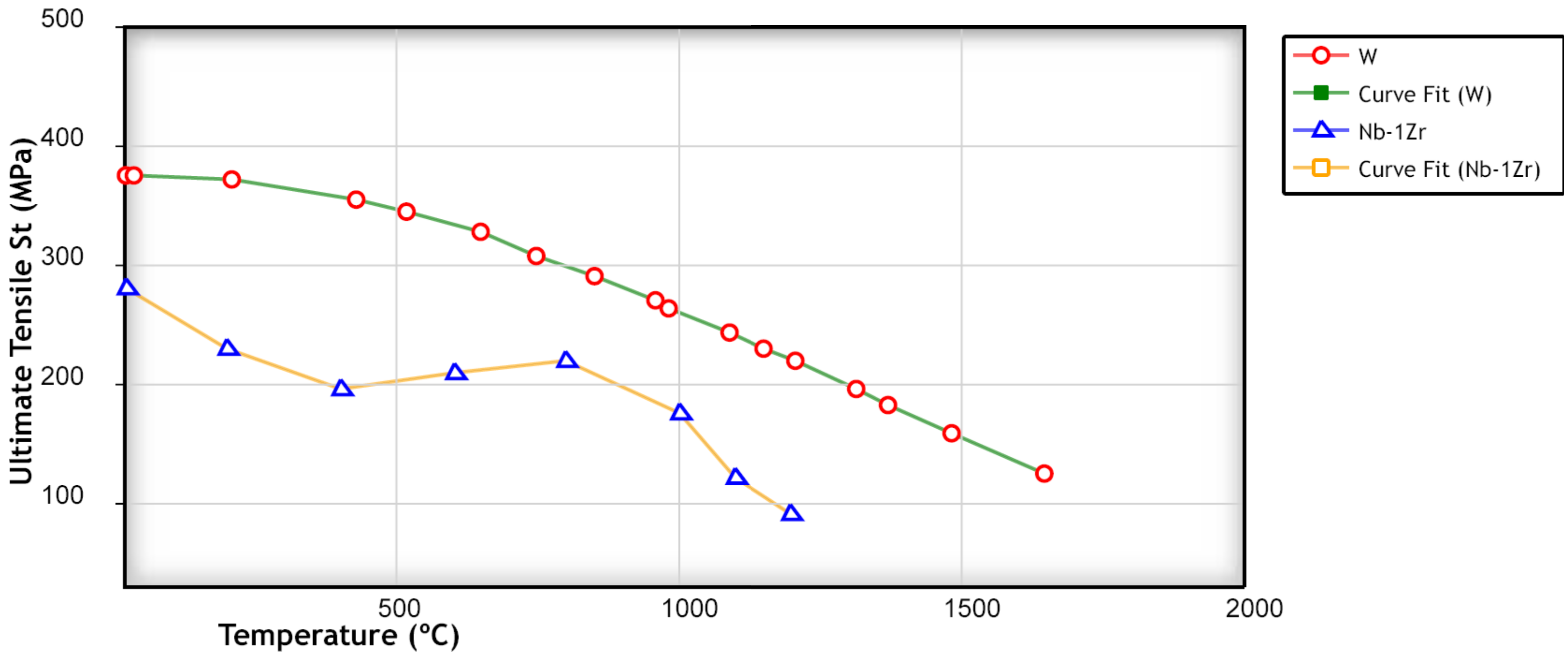
Material: Refractory Alloys and High-Conductivity Structural Alloys
Property: Ultimate Tensile Strength vs. Temperature
Condition: Un-Irradiated
Data: Experimental



Source:
APEX Study Meeting, Sandia National Laboratory (July 27-28, 1998)

Title of paper (or report) this figure appeared in:
Status of Recent Activities by the APEX Materials Group

Author of paper or graph:
S.J. Zinkle



Comparison of the Ultimate Strength of Recrystallized Refractory Alloys and High-Conductivity Structural Alloys

Reference:

Author: *S. J. Zinkle*

Title: *Status of Recent Activities by the APEX Materials Group*

Source: *APEX Study Meeting, Sandia National Laboratory (July 27-28, 1998)*, [PDF]

View Data | Author Comments

Plot Format:

Y-Scale: linear log ln

X-Scale: linear log ln

Update | Close Window

Status of Recent Activities by the APEX Materials Group

- **Physical Properties of Proposed Coolants and Structural Materials**
- **Estimated operating temperature limits**
- **Updated cost information**

S.J. Zinkle
Oak Ridge National Laboratory

presented at APEX Study Meeting
Sandia National Laboratory, July 27-28, 1998

Possible Structural Materials for High Wall Loading Concepts

- **Low-activation materials**
  - Vanadium alloys
  - Ferritic/martensitic (8-9%Cr) steels, ODS steels
  - SiC/SiC composites

- **Refractory alloys**
  - Nb-1Zr
  - Nb-18W-8Hf
  - T-111 (Ta-8W-2Hf)
  - TZM (Mo-0.5Ti-0.1Zr-0.02C)
  - Mo-Re
  - W-25Re

- **Ni-based superalloys**

- **Porous-matrix metals and ceramics**

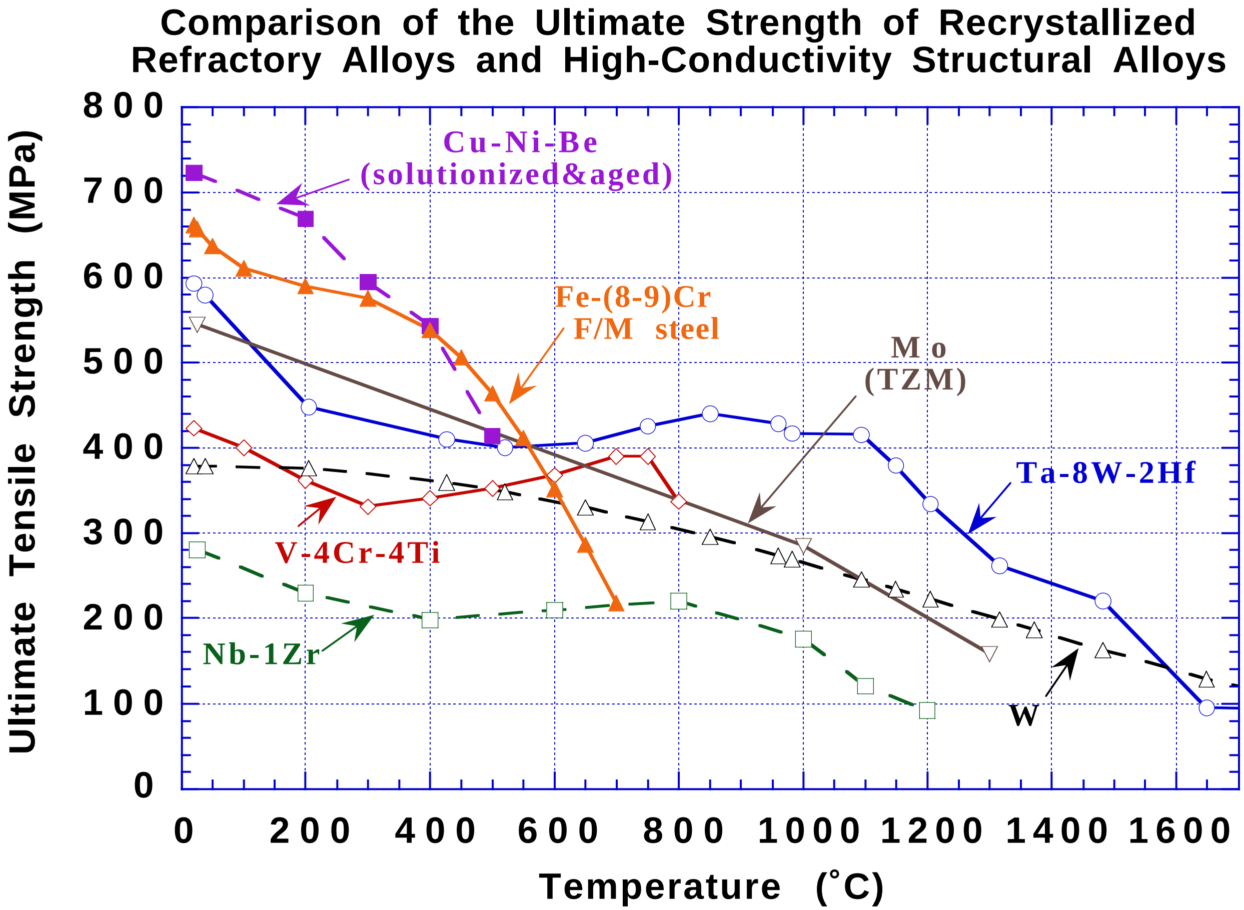
- **Intermetallics**
  - TiAl
  - Fe_3Al

- **Composites**
  - C/C
  - metal matrix composites
  - Cu-graphite
  - Ti_3SiC_2 composites

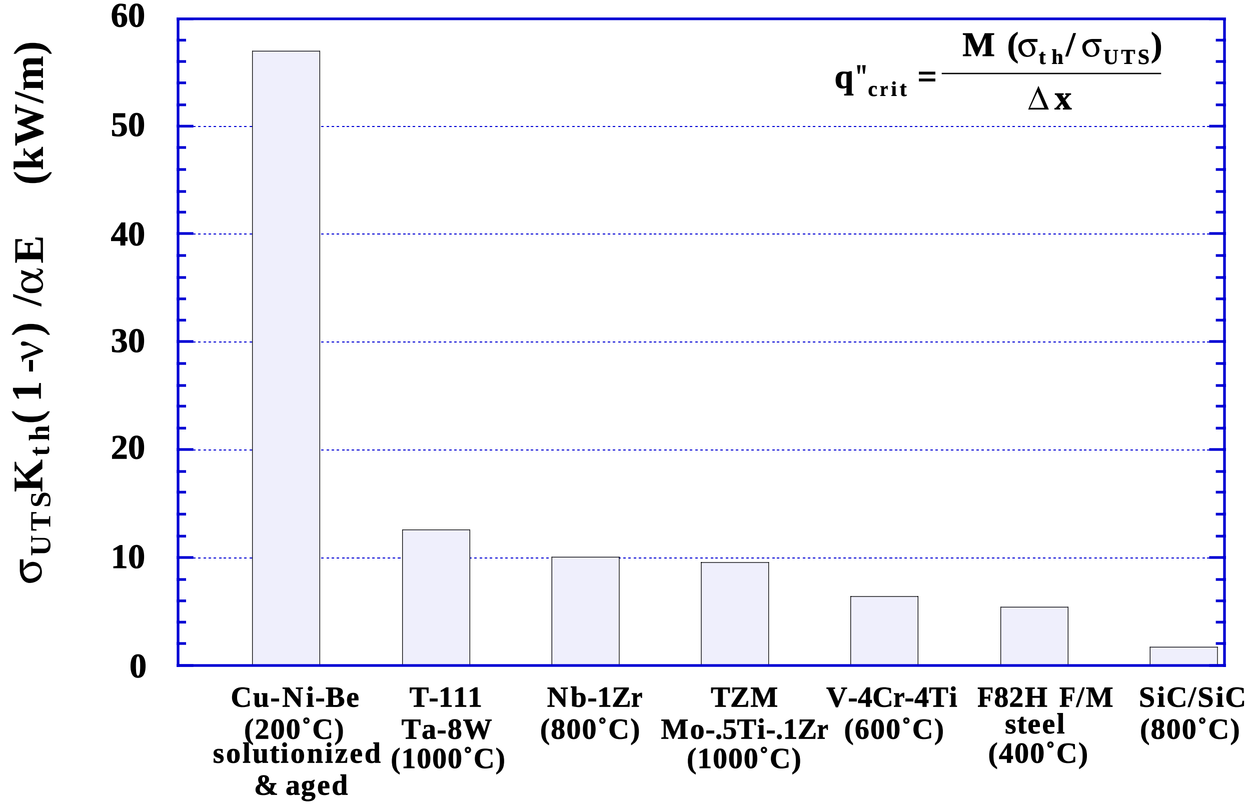
Factors Affecting Selection of Structural Materials

- **Unirradiatiated mechanical and thermophysical properties**
- **Chemical compatibility/corrosion effects**
- **Materials availability / fabricability / joining technology**
- **Radiation effects**
- **Safety aspects (decay heat, induced radioactivity, etc.)**

Data from Tietz & Wilson (1965), Conway (1984), Buckman (1994),
Zinkle et al (1998), ITER MPH, and Aerospace Structural Metals Handbook (1969)



COMPARISON OF THERMAL STRESS PARAMETERS FOR ANNEALED ALLOYS
(recrystallized Ta, Nb, Mo, V alloys; aged Cu alloy; tempered martensitic steel)



Resources for Structural Materials Database

- **Fusion Materials Properties Handbook / ITER Materials Properties Handbook, ed. J.W. Davis (Boeing/St Louis)**

  - V alloy chapter has NOT been updated in latest versions of IMPH (pubs. 4, 5)
  - limited or no information for F/M steels, SiC/SiC

- **Aerospace Structural Metals Handbook (1963-1988), ed. W.F. Brown, Jr.**
  - mechanical and thermophysical properties of refractory alloys vs. temperature

- **Proc. Conf. on Refractory Alloys for Space Nuclear Power Applications, eds. R.H. Cooper, Jr. and E.E. Hoffman, CONF-8308130 (1984)**

- **ITER Materials Assessment Report G A1 DDD 01 97-08-13 W01.1 (Chapter 2.2, W alloys)**

- **Original research publications**

Summary of V-4Cr-4Ti Properties

Ultimate Tensile Strength (unirradiated)

σ_{UTS}(MPa)= $446 - 0.806*T + 0.00221*T^2 - 1.79e\text{-}06*T^3 + 1.82e\text{-}10*T^4$ (T in ˚C)

Yield Strength (Unirradiated)

σ_Y(MPa)= $377 - 0.704*T + 0.00090*T^2 - 1.23e\text{-}07*T^3 - 1.98e\text{-}10*T^4$ (T in ˚C)

Elongation

e_{tot} , RA are high in unirradiated and irradiated conditions
e_u is high in unirradiated conditions, moderate (>2%) after irradiation at T>430˚C and low (<1%) for irradiation at T<400˚C

Elastic constants

E_Y (GPa) =128 - 0.00961*T (T in Kelvin)

G (GPa) =48.8 - 0.00843 *T (T in Kelvin) $\nu=(E_Y/2G) - 1$

Thermophysical properties

$\alpha_{th} = 9.03767 + 0.00301422*T + 4.95937\text{x}10^{-7} * T^2$ ppm/˚C (T in ˚C)

$C_P = 0.5755 - 21.1 / T$ J/g-K (T in Kelvin)

$k_{th} = 27.8 + 0.0086$ T W/m-K (T in Kelvin)

Recommended operating temperature limits (structural applications)

Tmin = 400˚C (due to rad.-induced increase in DBTT at low T_{irr})
Tmax = 700˚C (corrosion/chemical compatibility and thermal creep)

Summary of Recrystallized Ta-8W-2Hf (T-111) Properties

Ultimate Tensile Strength (unirradiated)

σ_{UTS}(MPa)=630 - 1.532*T +0.003388*T^2 -2.807e-06*T^3 +7.338e-10*T^4 (T in ˚C)

Yield Strength (Unirradiated)

σ_Y(MPa)= 612 - 1.743*T +0.003585*T^2 -3.076e-06*T^3 +8.819e-10*T^4 (T in ˚C)

Elongation

e_{tot} , RA are high in unirradiated and irradiated conditions
e_u is high in unirradiated conditions, moderate (>2%) after irradiation at T>650˚C and low (<1%) for irradiation at T<600˚C

Elastic constants (pure Ta)

E_Y (GPa) =169 - 0.00822*T - 1.66x10^{-6} T^2 (T in Kelvin)

G (GPa) =77.4 - 0.0173 *T (T in Kelvin) $\nu=(E_Y/2G) - 1$
ν=0.35 (300 K)

Thermophysical properties

α_{th} = 5.9 ppm/˚C (20˚C) and 7.6 ppm/˚C (1650˚C)

C_P = 150 J/kg-K (20˚C)

K_{th} (W/m-K)=41.0 + 0.020 T - 6.32x10^{-6} T^2 (T in ˚C)

Recommended operating temperature limits (structural applications)

Tmin = 650˚C (due to rad.-induced increase in DBTT at low T_{irr})
Tmax = 1200˚C (thermal creep)

Summary of 8-9Cr Ferritic/Martensitic Steel Properties

Ultimate Tensile Strength (unirradiated)

σ_{UTS}(MPa)= $683 - 1.162*T + 0.00547*T^2 - 1.17e-05*T^3 + 6.24e-09*T^4$ (T in ˚C)

Yield Strength (Unirradiated)

σ_Y(MPa)= $531 - 0.388*T + 0.00148*T^2 - 2.40e-06*T^3 - 1.45e-10*T^4$ (T in ˚C)

Elongation

e_{tot} , RA are moderate to high in unirradiated and irradiated conditions (e_{tot}~8-10% for T_{irr}<400˚C)
e_u is low in unirradiated (0.2-7%) and irradiated (<3%) conditions

Elastic constants

E_Y (GPa) =233 - 0.0558*T 20- 450˚C (T in Kelvin)

G (GPa) =90.1 - 0.0209 *T 20- 450˚C (T in Kelvin) $\nu=(E_Y/2G) - 1$

Thermophysical properties

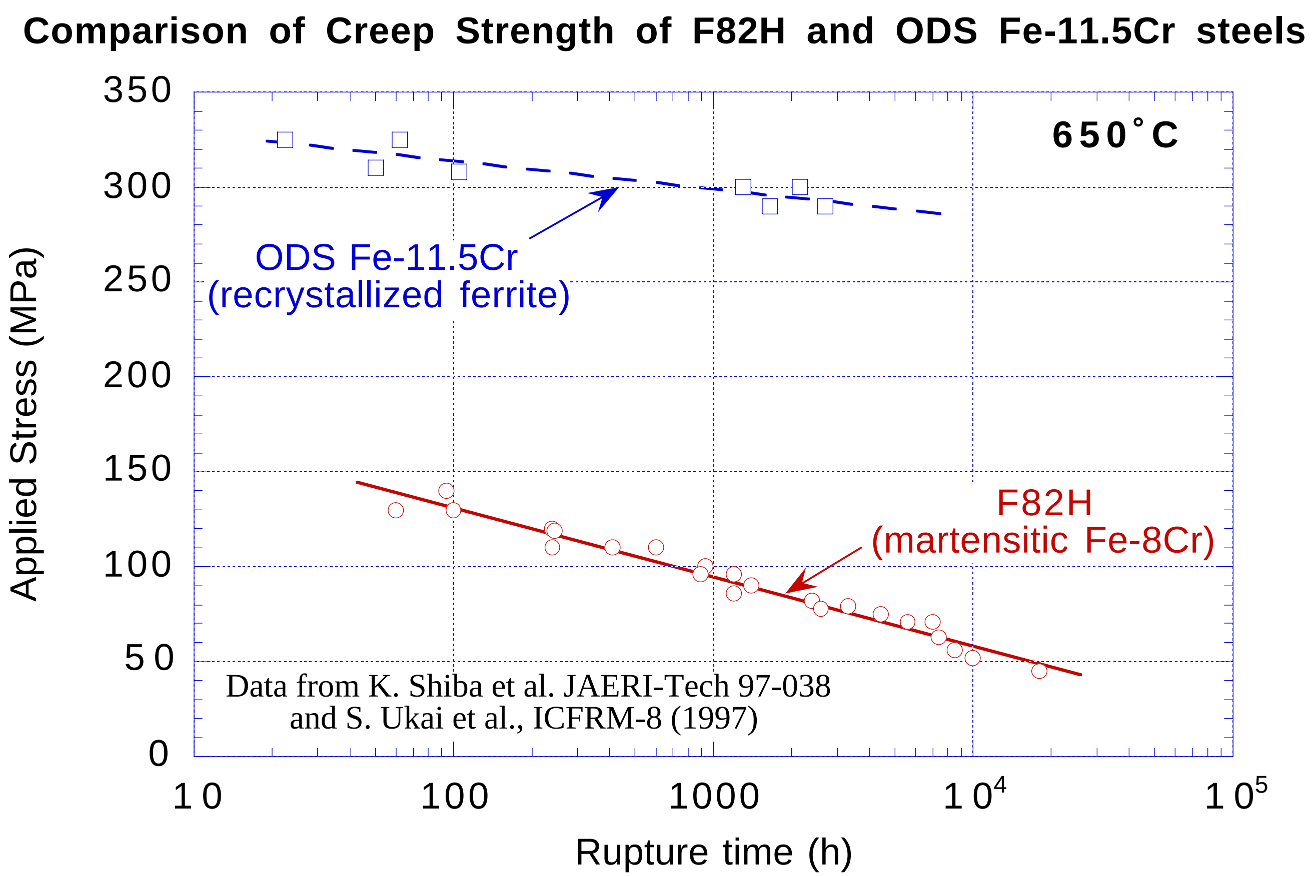
α_{th} = 10.4 ppm/˚C (20˚C) to 12.4 ppm/˚C (700˚C)

C_P = 0.47 J/g-K (20˚C) to 0.81 J/g-K (700˚C)

k_{th} = 33 W/m-K (20-700˚C)

Recommended operating temperature limits (structural applications)

Tmin = 250˚C (due to rad.-induced increase in DBTT at low T_{irr})
Tmax = 550˚C (thermal creep); Tmax~700˚C for ODS steels?



Comparison of Creep Strength of F82H and ODS Fe-11.5Cr steels
650°C
ODS Fe-11.5Cr
(recrystallized ferrite)
F82H
(martensitic Fe-8Cr)
Data from K. Shiba et al. JAERI-Tech 97-038
and S. Ukai et al., ICFRM-8 (1997)
Applied Stress (MPa)
Rupture time (h)
350
300
250
200
150
100
50
0
10
100
1000
10^4
10^5

Summary of SiC/SiC Properties

Ultimate Tensile Strength (unirradiated)

σ_{UTS} ~ 220-240 MPa (20-1000˚C)

Proportional Limit Strength (Unirradiated)

σ_Y(MPa) ~70 MPa (20-1000˚C)

Elongation

e_{tot} , eu, RA are very low in unirradiated and irradiated conditions

Elastic constants

E_Y GPa) ~400 GPa 20- 1000˚C (Sylramic or Hi-Nicalon type S fibers, 10% matrix porosity)

G (GPa) =~165 GPa 20- 1000˚C

ν=0.16 20- 1000˚C

Thermophysical properties

α_{th} ~ 2.5 ppm/˚C (20˚C) to 4.5 ppm/˚C (1000˚C)

C_P = $1110 + 0.15\ T - 425\ e^{-0.003T}$ J/kg-K (1000˚C)

k_{th} = 10-15 W/m-K (400-1000˚C, after irradiation)

Recommended operating temperature limits (structural applications)

Tmin ~ 400˚C (due to rad.-induced decrease in thermal conductivity)
Tmax = 1000˚C? (due to cavity swelling)

Summary of Recrystallized Tungsten Properties (from IMPH)

Ultimate Tensile Strength (unirradiated)

σ_{UTS}(MPa)=377.9 + 0.03207*T - 1.955x10^{-4}*T^{2} + 5.129x10^{-8}*T^{3} (T in ˚C)

Yield Strength (Unirradiated)

σ_{Y}(MPa)= 94.2 - 0.0214*T -2.12x10^{-4}*T^{2} -7.48x10^{-10}*T^{3} (T in ˚C)

Elongation

e_{tot}(%)=20.8 + 0.053*T-2.18x10^{-5}*T^{2} (T>500˚C)

Elastic constants

E_{Y} (GPa) =398 - 0.00231*T - 2.72x10^{-5} T^{2} (T in ˚C)

ν=0.279 + 1.09x10^{-5} T (T in ˚C)

Thermophysical properties

α_{m} (10^{-6}/˚C)= 3.922 + 5.835x10^{-5}*T + 5.705x10^{-11}*T^{2} - + 2.046x10^{-14}*T^{3} (T in ˚C)

C_{P} (J/kg-K) = 128.3 + 0.0328*T - 3.41x10^{-6}*T^{2} (T in ˚C)

K_{th} (W/m-K)=174.9 - 0.107 T + 5.01x10^{-5} T^{2} - 7.835x10^{-9}*T^{3} (T in ˚C)

Recommended operating temperature limits (structural applications)

Tmin = 800˚C (due to rad.-induced increase in DBTT at low T_{irr})

Tmax = 1400˚C (corrosion/chemical compatibility and thermal creep)

Chemical Compatibility of High Temperature Refractory Alloys with Liquid Metals and FLiBe

- In general, the refractory alloys have very good compatibility with the liquid metals and salts of interest for fusion applications
  - impurity pickup is the key engineering issue

- Li chemical compatibility data base (to be discussed by Nasr Ghoniem):

  T-111 (Ta-8W-2Hf) data up to 1370˚C (good compatibility; static and circulating loops)

  Nb-1Zr data up to 1000˚C (good compatibility; static and circulating loops)

  W alloys up to 1370˚C (attack observed at ≥1540˚C)

  Mo alloys (TZM) up to 1370˚C (attack observed at ≥1540˚C)

- Chemical compatibility data base for FLiBe will be presented by Dai-Kai Sze (generally good compatibility with proposed structural metals)

Maximum temperatures of structural alloys (bare walls) in contact with high-purity liquid coolants, based on a 5 μm/yr corrosion limit

	Li	Pb-17 Li	Flibe
F/M steel	550-600°C [1,2,3]	450°C [1,2,9]	700°C ? 304/316 st. steel [13]
V alloy	600-700°C [1,4,5]	~650°C [1,10]	?
Nb alloy	>1300°C [6,7]	>600°C [10] (>1000°C in Pb) [11]	>800°C [14]
Ta alloy	>1370°C [6,7]	>600°C [10] (>1000°C in Pb) [11]	?
Mo	>1370°C [6,7]	>600°C [10]	>1100°C? [15,16]
W	>1370°C [6,7]	>600°C [10]	>900°C? [15]
SiC	~550°C ? [8]	>800°C ? [12]	?

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Overview of Radiation Effects in Refractory Metals

- Void swelling is not anticipated to be a lifetime-limiting issue due to the BCC structure of the high-temperature refractory alloys
  - existing fission reactor data base indicate low swelling (<2%) for doses up to 50 dpa or higher
  - effects of fusion-relevant He generation on swelling is uncertain
  - swelling regimes are ~600 to 1000˚C for all 4 classes of refractory alloys

- The Group Vb alloys (Nb, Ta) exhibit better ductility before and after irradiation
  - very limited mechanical properties data base on irradiated Nb, Ta alloys
  - extensive mechanical properties data base on irradiated Mo, W alloys

- Very limited or no fracture toughness/Charpy impact data on irradiated high temperature refractory alloys

  - "tensile DBTT" of Mo, W alloys increases to very high values even for low dose irradiations at moderate temperatures (e.g., 600˚C after ~1 dpa irradiation at 300˚C for W, W-10Re)

- Refractory alloys are generally designed for use in stress-relieved condition (rather than recrystallized) in order to achieve of higher strength
  - radiation-enhanced recrystallization and/or radiation creep effects need to be investigated (designs should use recrystallized strengths to be conservative)

Radiation Effects on Mechanical Properties of High-Temperature Refractory Alloys

Ta Alloys: T-111 (Ta-8W-2Hf)

- Significant radiation hardening at 415, 640˚C (σ_y, UTS>1000 MPa) after 1.9×10^{26} n/m^2, E>0.1 MeV (2.5 dpa Ta, 10 dpa steel) --Wiffen 1984

- Very little radiation hardening at 800˚C, 2.5 dpa (Gorynin 1992)

=> estimated minimimum operating temperature ~650˚C, based on DBTT considerations

Mo Alloys: TZM (largest irradiated data base among high temperature refractories)

- Pronounced radiation hardening up to ~800˚C, 7-34 dpa (Hasegawa et al. 1996)

- Tensile elongation ~0 for T_{irr}< 700˚C, 5-20 dpa (Chakin&Kazakov 1996, Fabritsiev & Pokrovsky 1998)

=> estimated minimimum operating temperature ~750˚C, based on DBTT considerations

W and W Alloys: P/M or CVD W, W-1% La_2O_3, W-Mo-Y (alloy W-13I)

- Tensile elongation ~0 for T_{irr}= 400, 500˚C, 0.5-1.5×10^{26} n/m^2, $\leq$2 dpa (Wiffen 1984, Gorynin et al 1992); irradiations at 700˚C are in progress

=> estimated minimimum operating temperature ~800˚C, based on DBTT considerations (scaling from Mo alloy data base)

Updated Cost Information (~1996 prices)

Material	Cost per kg
Fe-9Cr steels	≤$5.50 (plate form)
SiC/SiC composites	>$1000 (CVI processing) ~$200 (CVR processing of CFCs)
V-4Cr-4Ti	$200 (plate form--average between 1994-1996 US fusion program large heats and Wah Chang 1993 "large volume" cost estimate)
Nb-1Zr	~$100
Ta	$300 (sheet form)
Mo	~$80 (3 mm sheet); ~$100 for TZM
W	~$200 (2.3 mm sheet); higher cost for thin sheet

Estimated Operating Temperature Limits for Refractory Alloys in Fusion Reactors