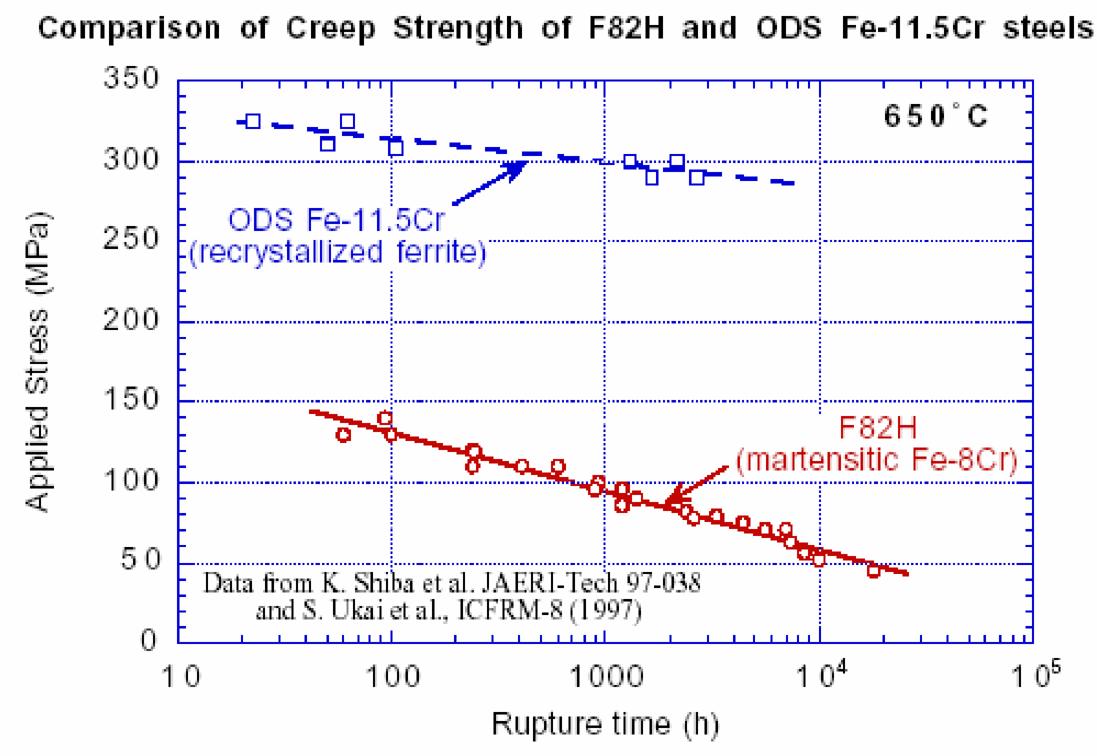
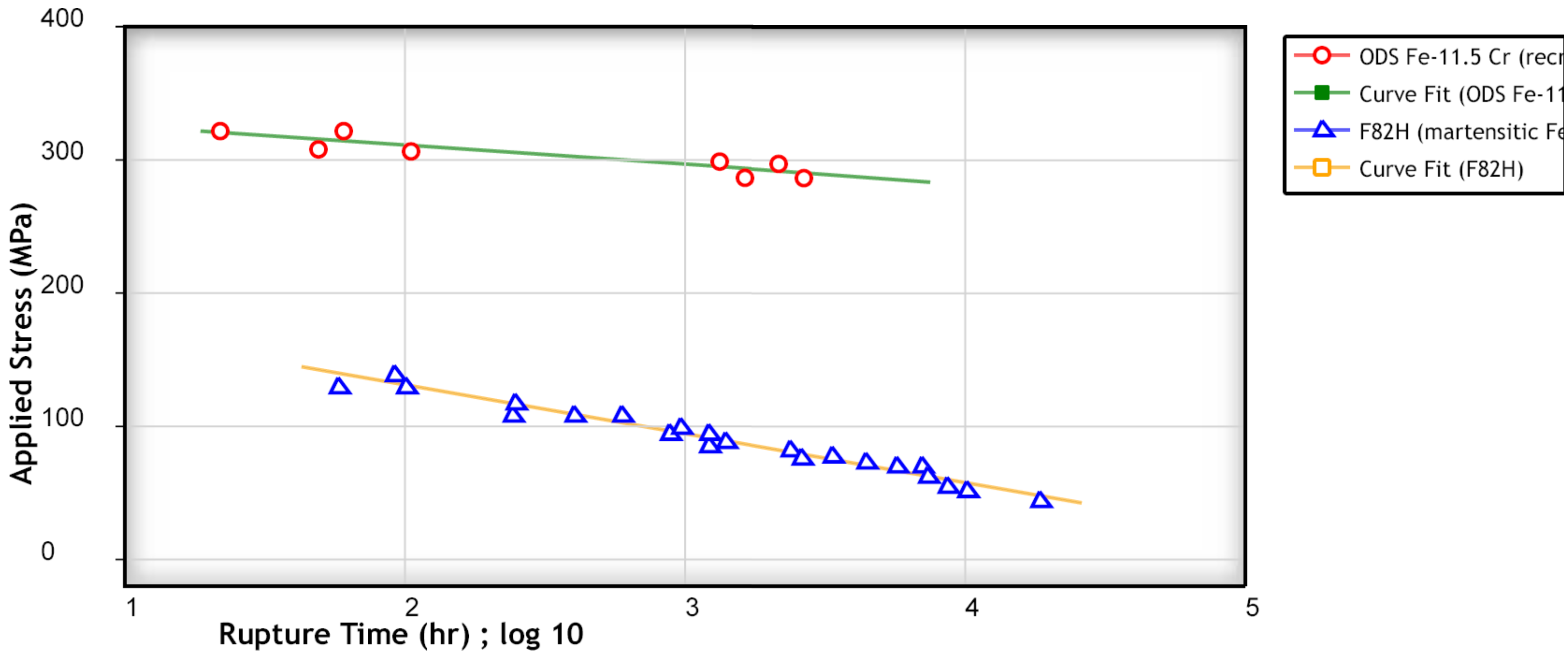
Material: F82H and ODS Fe-11.5Cr steels
Property: Applied Stress vs. Rupture time
Condition: Un-Irradiated
Data: Experimental



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 Creep Strength of F82H and ODS Fe-11.5Cr steels (650ºC)

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**

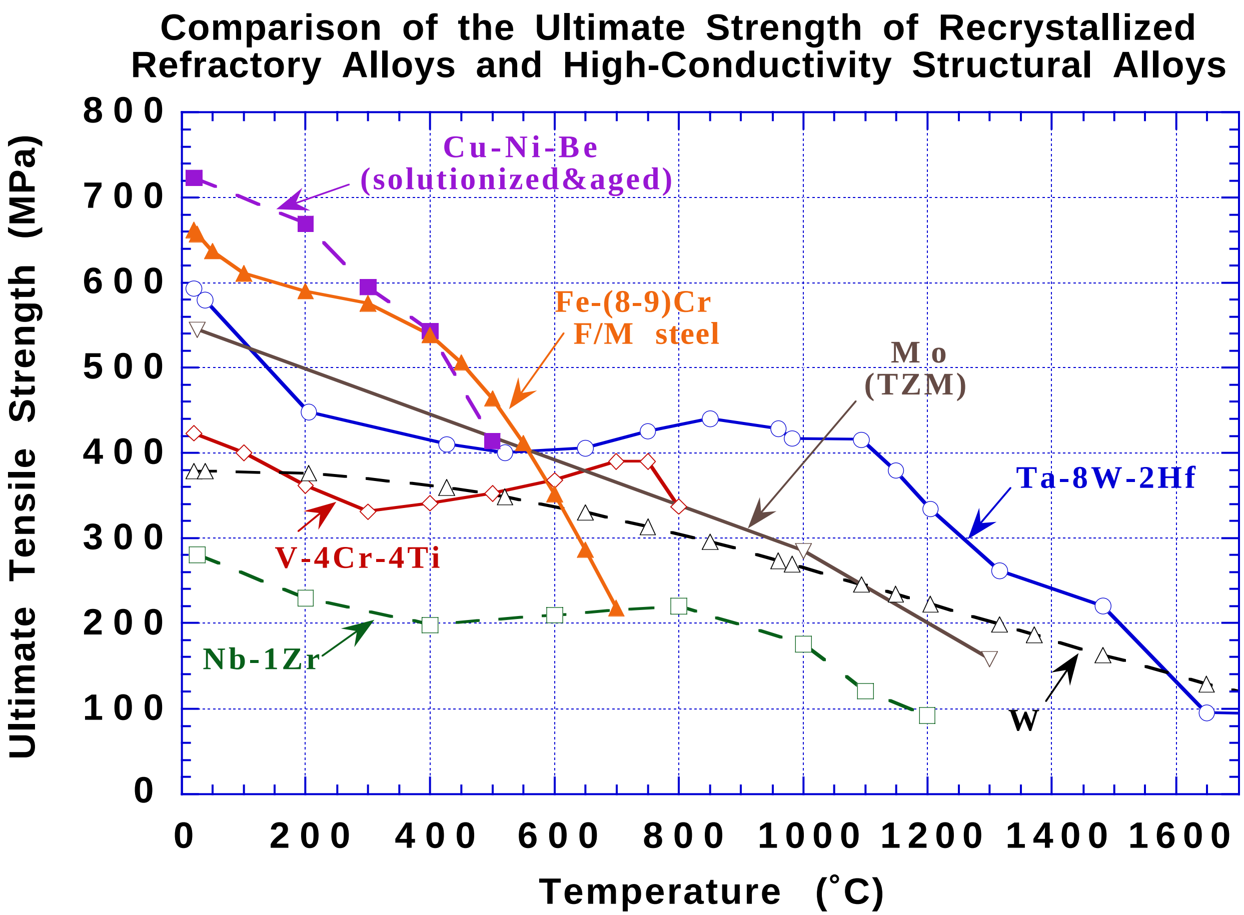
- **Intermetallics**
  - TiAl
  - Fe_3Al

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

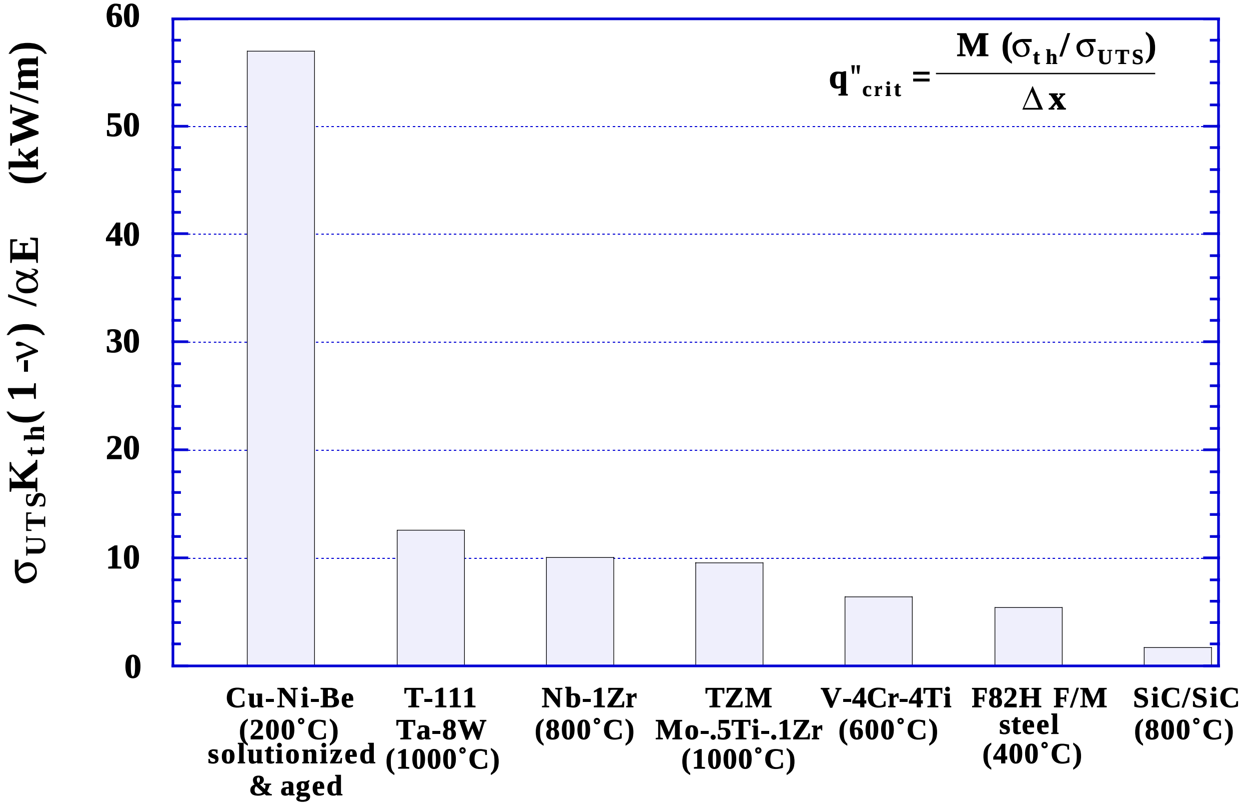
Factors Affecting Selection of Structural Materials

- **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-06*T^3 + 1.82e-10*T^4 (T in ˚C)

Yield Strength (Unirradiated)

σ_Y(MPa)= 377 - 0.704*T + 0.00090*T^2 - 1.23e-07*T^3 - 1.98e-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

α_{th} = 9.03767 + 0.00301422*T + 4.95937x10^{-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)

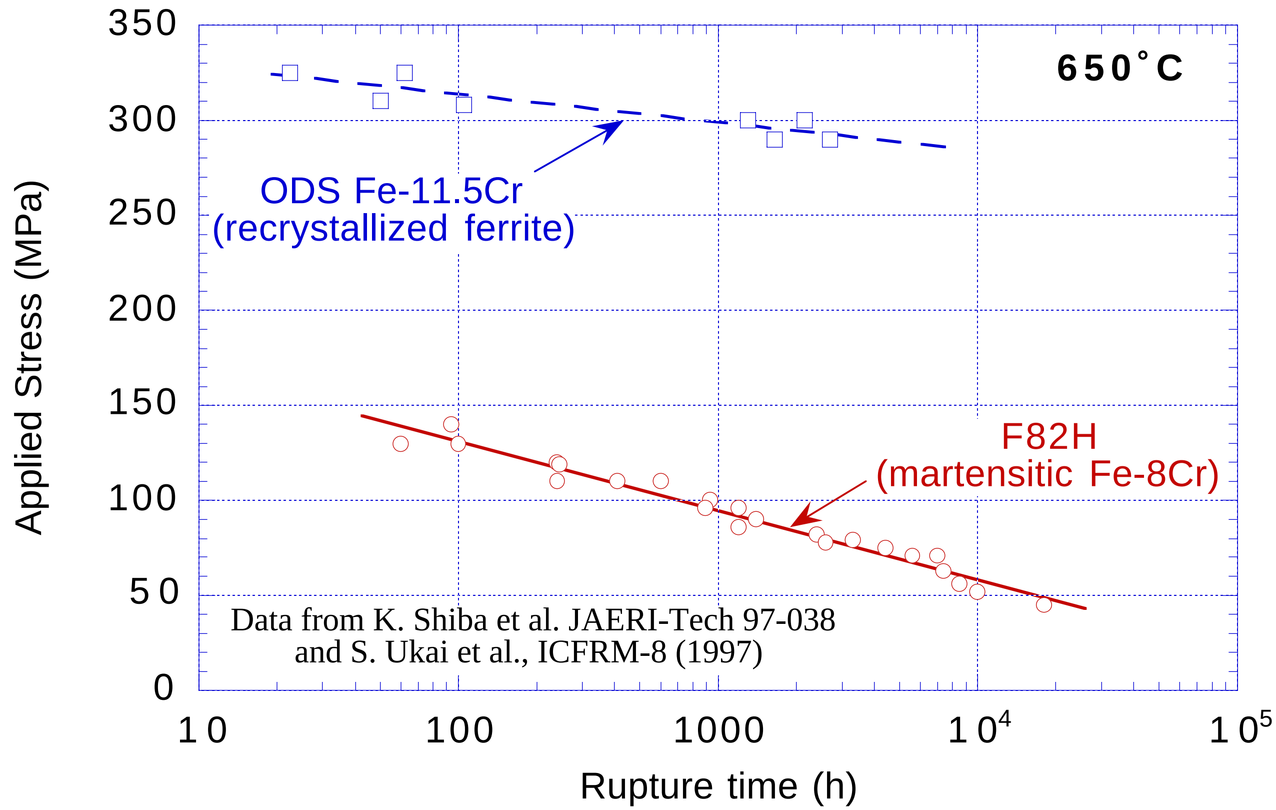
C_P = 0.47 J/g-K (20˚C) to 0.81 J/g-K (700˚C)

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



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]	?

References:

1. S. Malang and R. Mattas, Fus. Eng. Des. 27 (1995) 399.
2. O.K. Chopra and D.L. Smith, J. Nucl. Mater. 155-157 (1988) 715.
3. P.F. Tortorelli, J. Nucl. Mater. 155-157 (1988) 722.
4. K. Natesan et al., Fus. Eng. Des. 27 (1995) 457.
5. O.K. Chopra and D.L. Smith, J. Nucl. Mater. 155-157 (1988) 683.
6. J.H. Devan et al., Proc. Symp. on Refractory Alloy Technology for Space Nuclear Power Applications, CONF-8308130 (1984) p. 34.
7. J.R. DiStefano, J. Mater. Eng. 11 (1989) 215.
8. D.R. Curran and M.F. Amateau, Am. Ceram. Soc. Bulletin 65, 10 (1986) 1419.
9. M. Broc et al., J. Nucl. Mater. 155-157 (1988) 710.
10. H. Feuerstein et al., J. Nucl. Mater. 233-237 (1996) 1383.
11. H. Shimotake et al., Trans. ANS 10 (1967) 141.
12. P. Hubberstey and T. Sample, J. Nucl. Mater. 248 (1997) 140.
13. J.R. DiStefano, ORNL/TM-12925/R1 (1995).
14. W.D. Manley, Prog. Nucl. Energy, Series IV, 2 (1960) 164.
15. Y. Desai et al., Journal of Metals 40, 7 (1988) A63.
16. J.W. Koger and A.P. Litman, ORNL/TM-2724 (1969).

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, $0.5\text{-}1.5 \times 10^{26}$ 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