DESIGN WINDOW FOR TUNGSTEN ALLOYS

S. Sharafat , R. Martinez
N. M. Ghoniem

The University of California at Los Angeles (UCLA)
Los Angeles, CA. 90095-1597, USA

APEX STUDY GROUP MEETING

PPPL

May 12-14, 1999

PRESENTATION OUTLINE

- High Temperature Creep Strength Limits of W-Alloys
- Effects of Fabrication, Alloying, and Irradiation on the DBTT of W-Alloys.
- Estimates for DBTT Shifts based on a Phenomenological Model
- Oxidation limits for 1ppm O_2
- Recommendations of Design Windows for W-Alloys

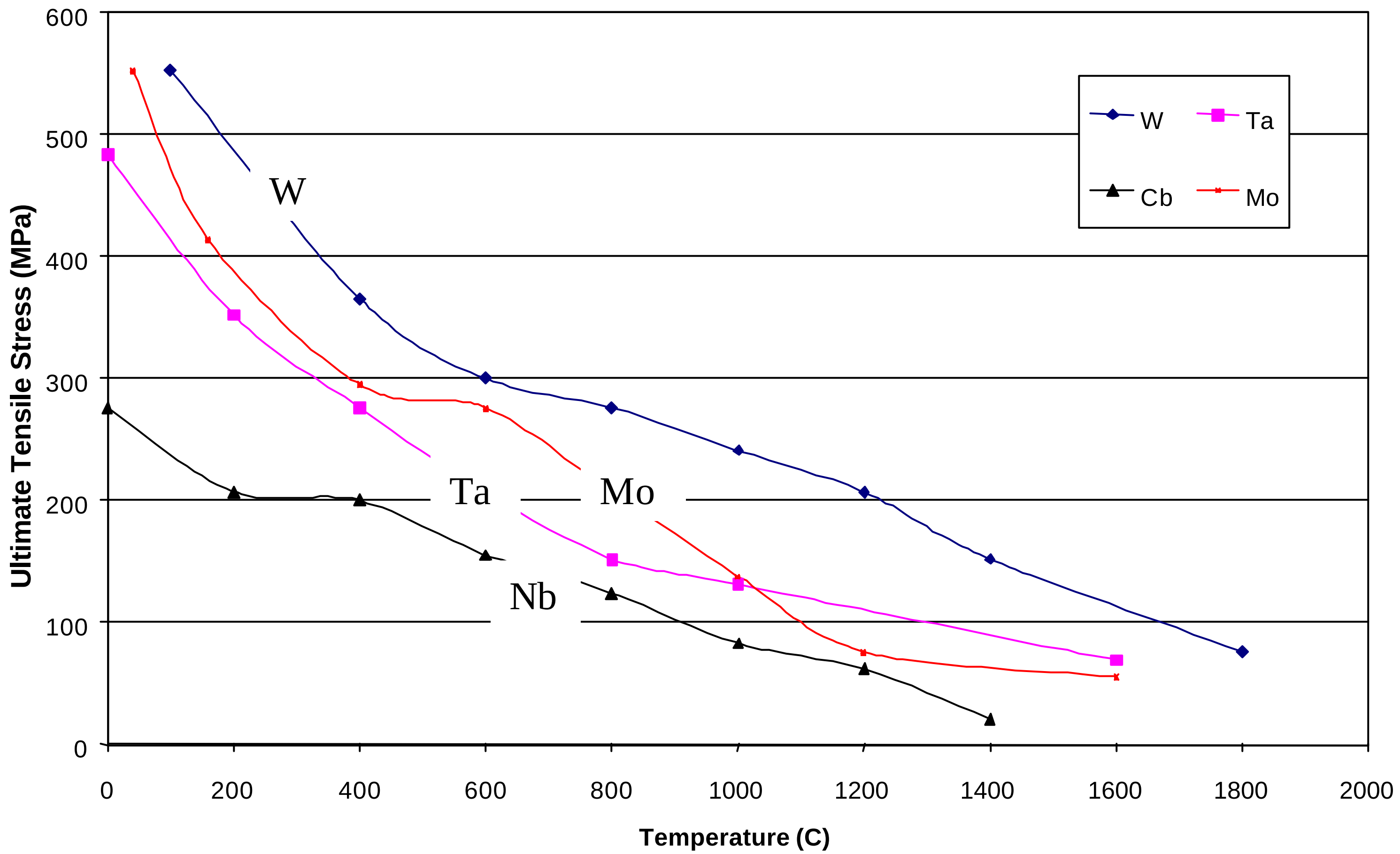
Physical and Mechanical Properties of ITER Considered W-Alloys Unirradiated Properties

After: J. Smid, et al., J. Nucl. Mater. 258-263(1998)160

...d mechanical properties of some high-Z and heat-sink materials

	W	W–1%La_2O_3	W–5%Re	W–30Cu ~50 vol% W	W–Ni–Fe ~95 wt% W	W–Ni–Cu ~95 wt% W
Density at RT, g/cm^3	19.3	18.9	19.4	14.0	18.0	18.0
Thermal expans. coeff. at RT, 10^{-6}/K	4.5	4.7	4.5	11.5	5.5	5.2
Thermal cond. at RT/1000°C, W/mK	145/113	120/98	70/83	300/~220	83/-	108/-
Elastic modulus at RT, GPa	410	~410	400	218	380	350
Ultimate strength at RT, MPa	1000	900	1100	520	850	680
Poisson ratio	0.28	(0.3)	0.3	0.3	~0.3	~0.3
Tensile elongation at RT/1000°C, %	<0.4/25–30	<0.4/25–30	~1/13	~3/	16/	3/
Specific heat at RT, J/gK	0.14	0.14	0.14	0.24	0.19	0.18
DBTT, °C	100 ~ 400	~ as W	50 ~ 200	(<RT)	(<RT)	(<RT)
Recrystallization temperature, °C	1150–1350	1250–1700	>1500			
Melting point, °C	3410	~ as W	~3300	1080(Cu)	~1400	~1050
Max. temperature of application	≤ 3410	~ as W	(≤ 3300)	$<T_{melt}$	$\ll T_{melt}$	$\ll T_{melt}$
Vapor pressure at 2000°C, Pa	1.3×10^{-7}	> as W	≥ as W	(Cu)	(Ni)	(Cu)
Atomic number	74	(74)	(74)	(49)	(67)	(68)
Atomic weight	183.8	(183.)	(184)	(117)	(166)	(167)
Cross section for thermal neutrons, *b*	18.5	(18.)	(21.8)	(10.4)	(16.3)	(16.5)
Estimated neutron leakage (W = 100%)	1.0	~1.0	~1.0	0.5	0.8	0.85
Estimated costs: (as of late 1997)						
Material, US$/kg	~150	W, +20%	~400			
Machining	High	Low	Medium	Low	Low	Low
Joining possible:						
Brazing	Yes	Yes	Yes	Yes	Yes	Yes
Welding	No (?)	No	No ?	No	No	No

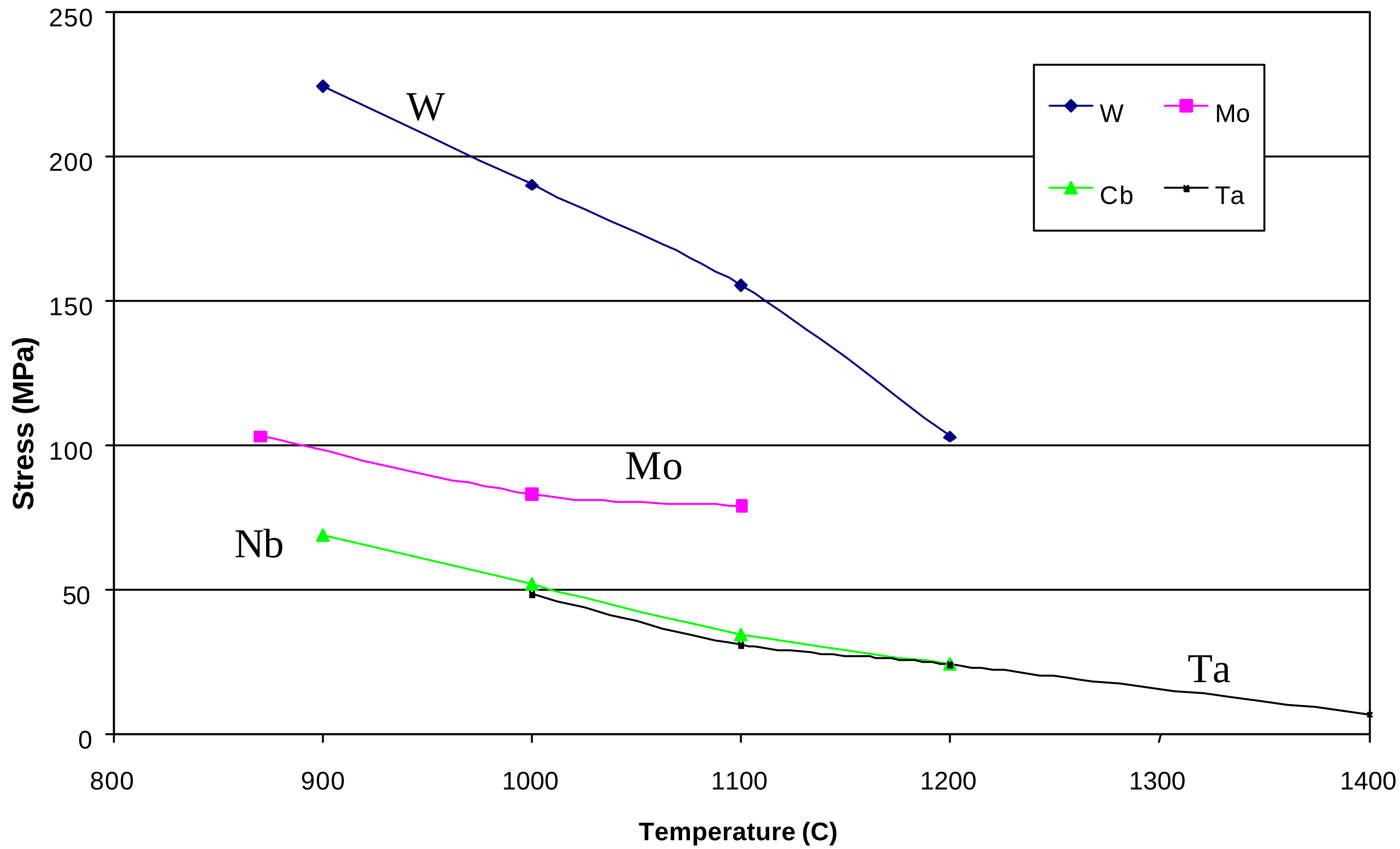
COMPARISON OF TENSILE BEHAVIOR OF REFRACTORY METALS



Reference: Tietz, Behavior and Properties of Refractory Metals, Stanford Press, Stanford, p. 195

HIGH TEMPERATURE CREEP STRENGTH OF REFRACTORY METALS

(100 Hour Test Results)



Reference: Tietz, Behavior and Properties of Refractory Metals, Stanford Press, Stanford, p. 195

HIGH TEMPERATURE CREEP STRENGTH LIMITS

- Limited data base requires the use of Larson Miller parameters (m) to correlate Temperature (T) with the time to failure (t_r)at constant engineering stress (s):

$$\boxed{T(\log t_r + C) = m}$$

MATERIAL	*LARSON-MILLER C*
Various Steels	~20
S-590 Alloys	17
A-286 SS	20
Nimonic 81A	18
1-Cr-1Mo-0.25V Steel	22

Ref.: M. A. Meyers, “Mechanical Behavior of Materials,” Prentice Hall, UK, 1998, p. 550.

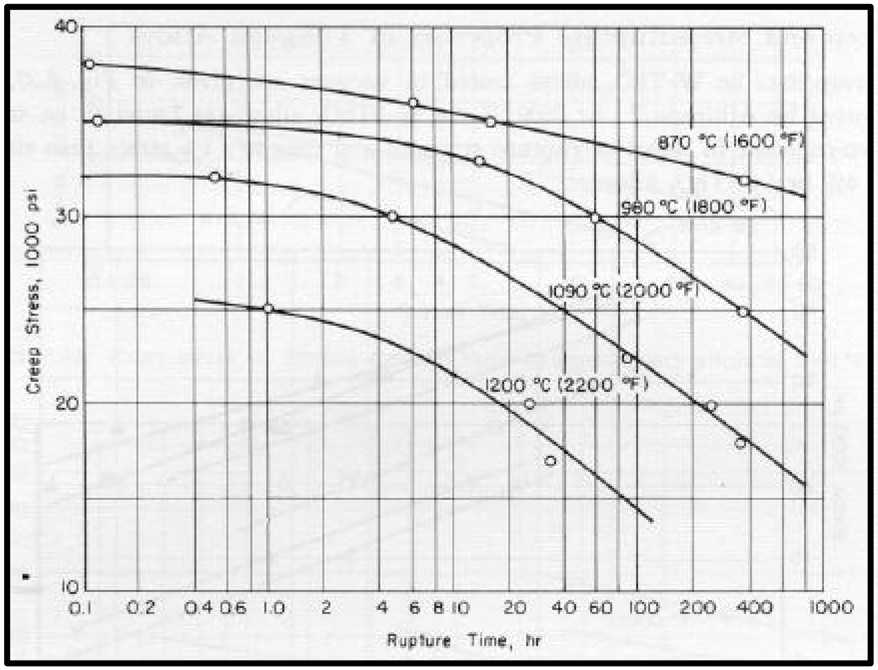
DESIGN STRESS LIMITS

- A simplified TENSILE DESIGN STRESS can be defined as the minimum value of 1/3 of the ULTIMATE or 2/3 of the YIELD strength, which ever is smaller:

$$\boxed{s_{design} = \min\left\{ \frac{1}{3} s_{ultimate} ; \frac{2}{3} s_{yield} \right\}}$$

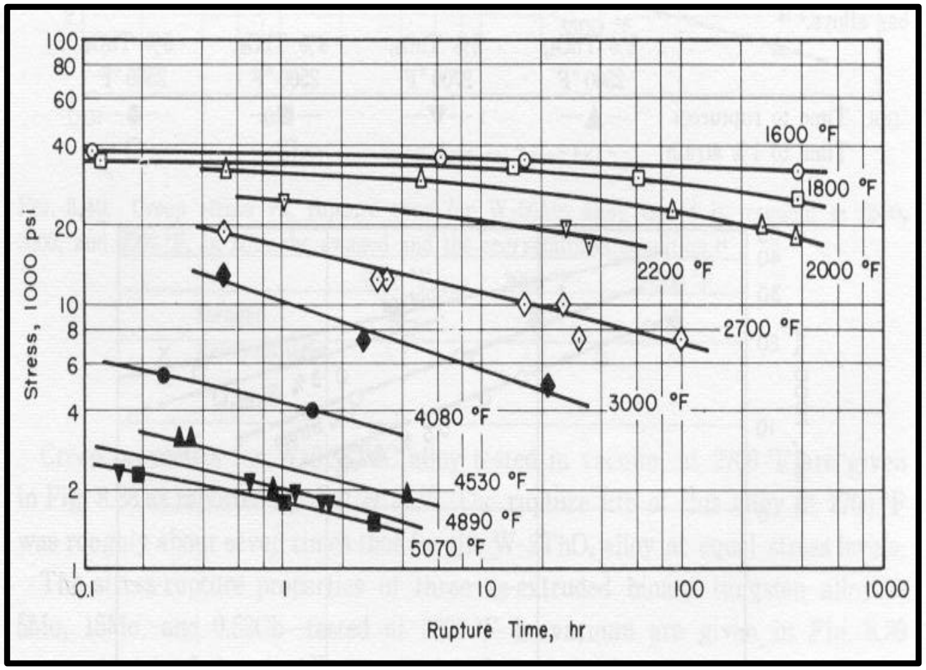
THE DESIGN-STRESS LIMIT IS CHOSEN TO BE THE LESSER OF THE 10 year CREEP STRESS LIMIT AND THE TENSILE STRESS-LIMIT $s_{\mathbf{design}}$.

CREEP-RUPTURE DATA OF PURE W



Creep stress vs. Rupture time for recrystallized tungsten at four temperatures

(Tietz, T.E., "Behavior and Properties of Refractory Metals," Stanford Press, CA, 1965, p. 315)

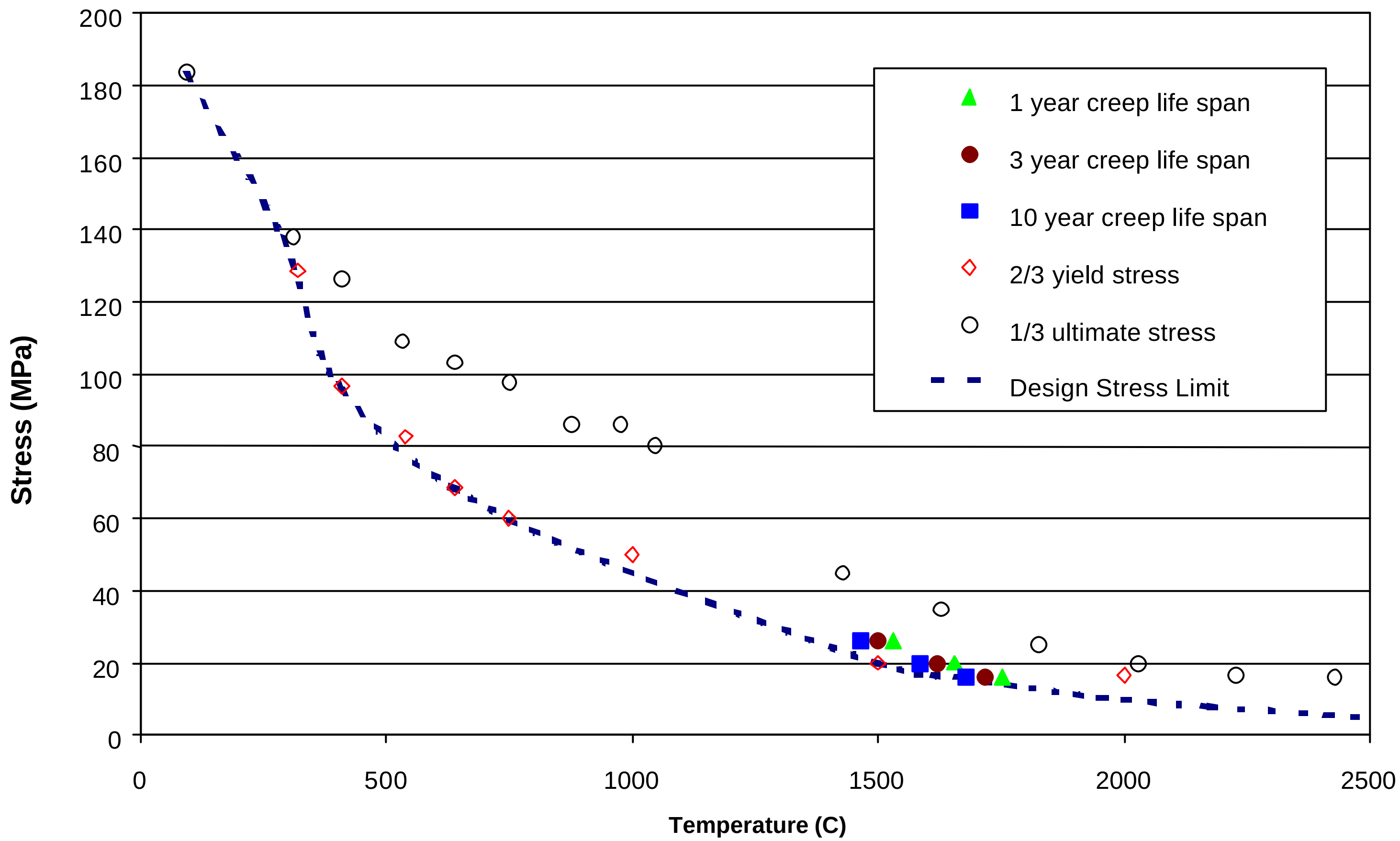


Creep stress vs. Rupture time for recrystallized tungsten in inert atmosphere.

(Tietz, T.E., "Behavior and Properties of Refractory Metals," Stanford Press, CA, 1965, p. 315)

LARSON-MILLER BASED CREEP-RUPTURE OF PURE W

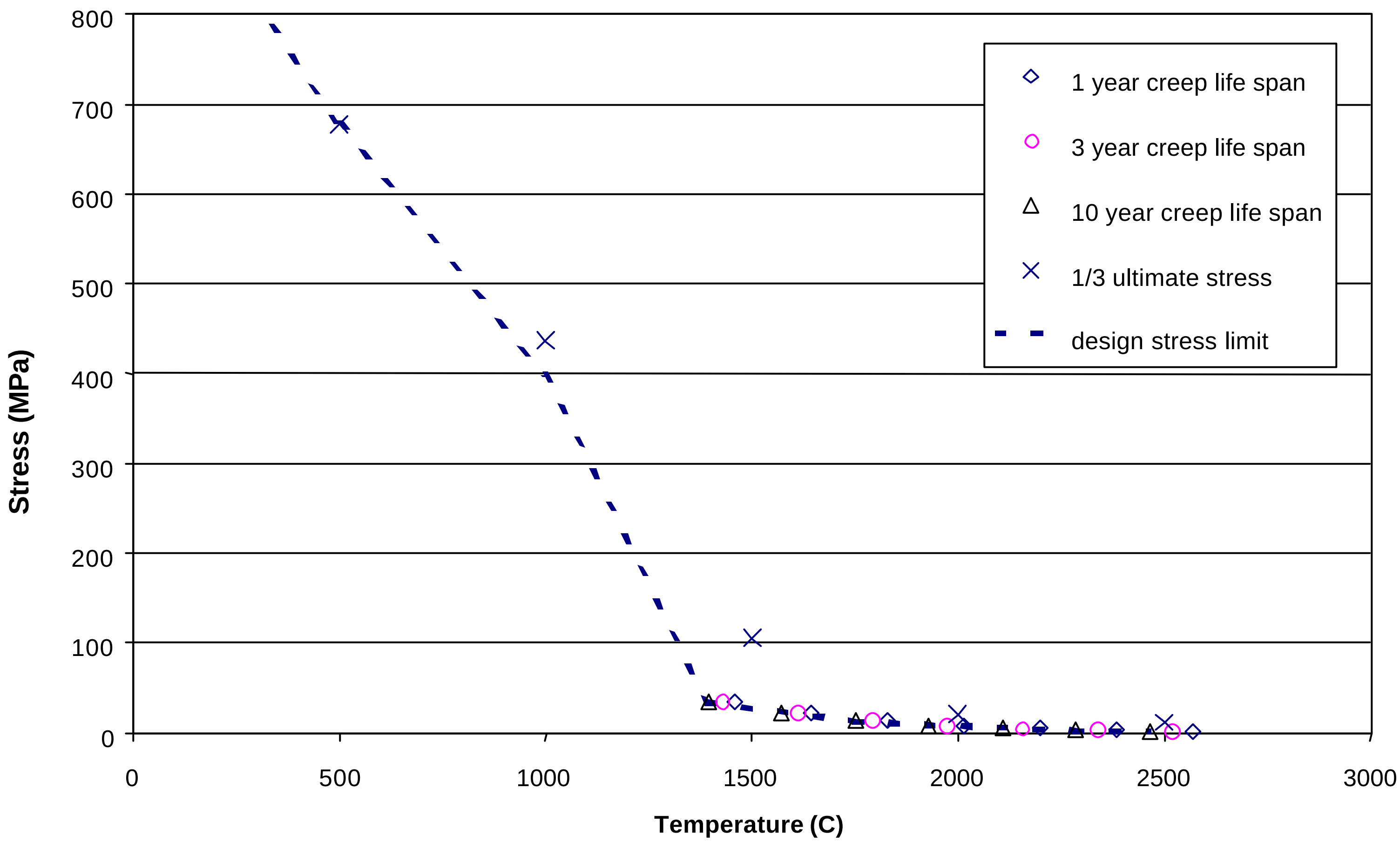
(Arc-Melted, Recrystallized)



References: Sims, “Properties of Refractory Alloys Containing Rhenium”, Trans. ASM, 52 (1960) p. 929- 941
Shin, “High Temperature Properties of Particle Strengthened W-5Re”, JOM August 1990, p. 12-15

LARSON-MILLER BASED CREEP-RUPTURE OF PURE W

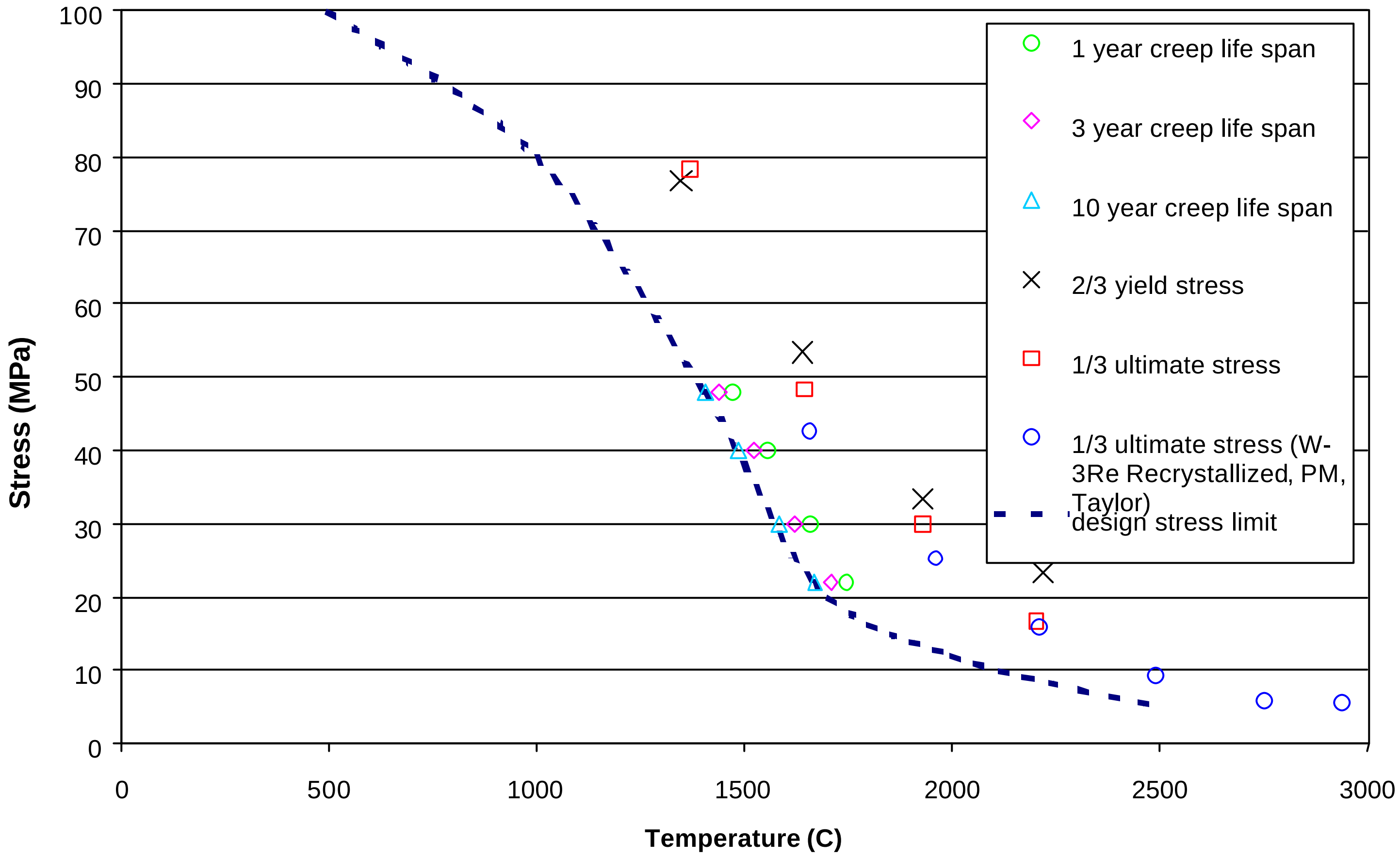
(Wrought, Arc-Cast, Tested in Hydrogen)



References: Tajime, “The Tensile Strength of Tungsten Wires at High Temperatures”, Hantaro Nagaoka Anniversary Volume, Tokyo (1925); Flagella, “High Temperature Creep Rupture Behavior of Unalloyed Tungsten”, GE-NMPO, GEMP-543

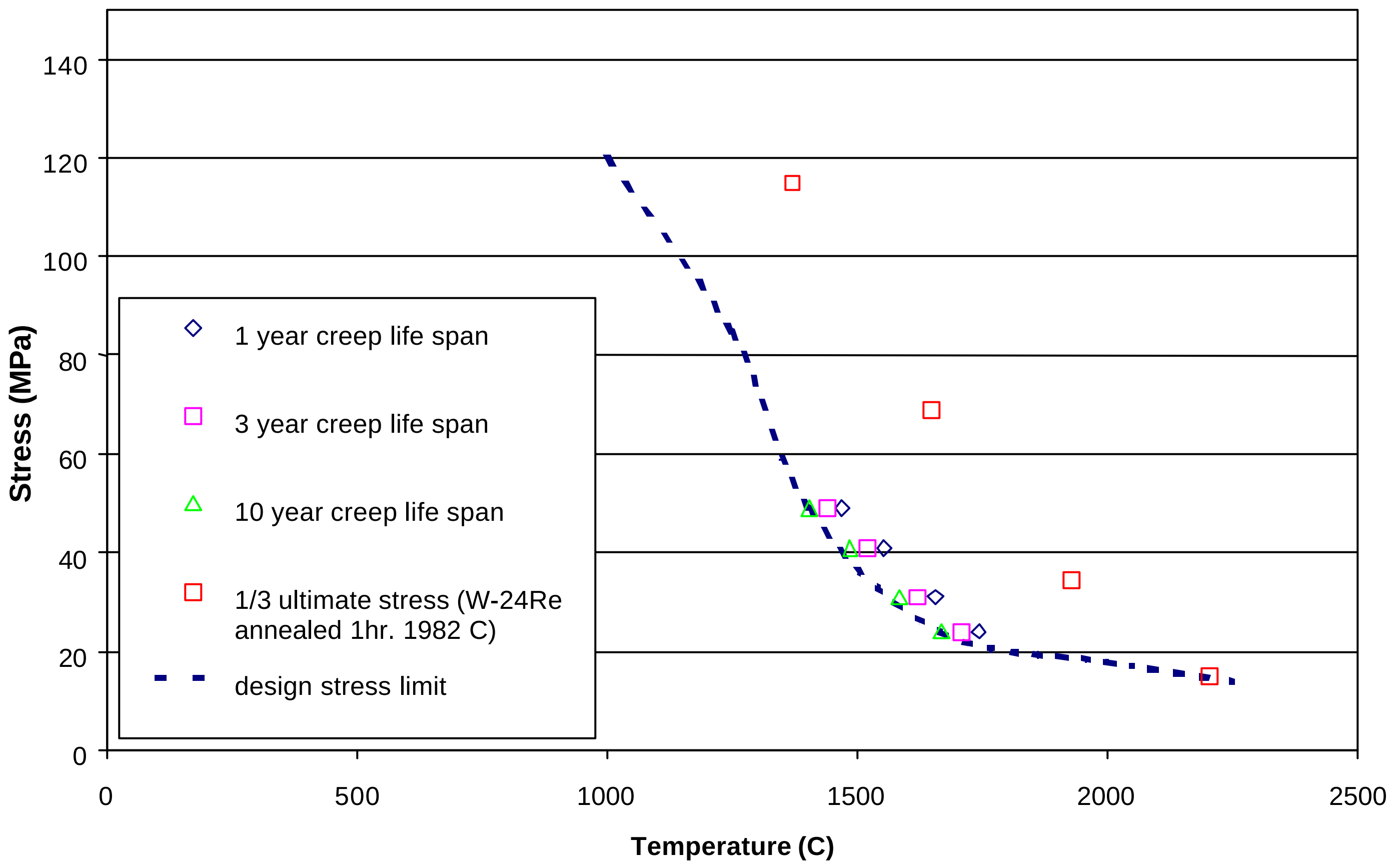
LARSON-MILLER BASED CREEP-RUPTURE OF W-5Re

(Arc-Melted, Recrystallized)



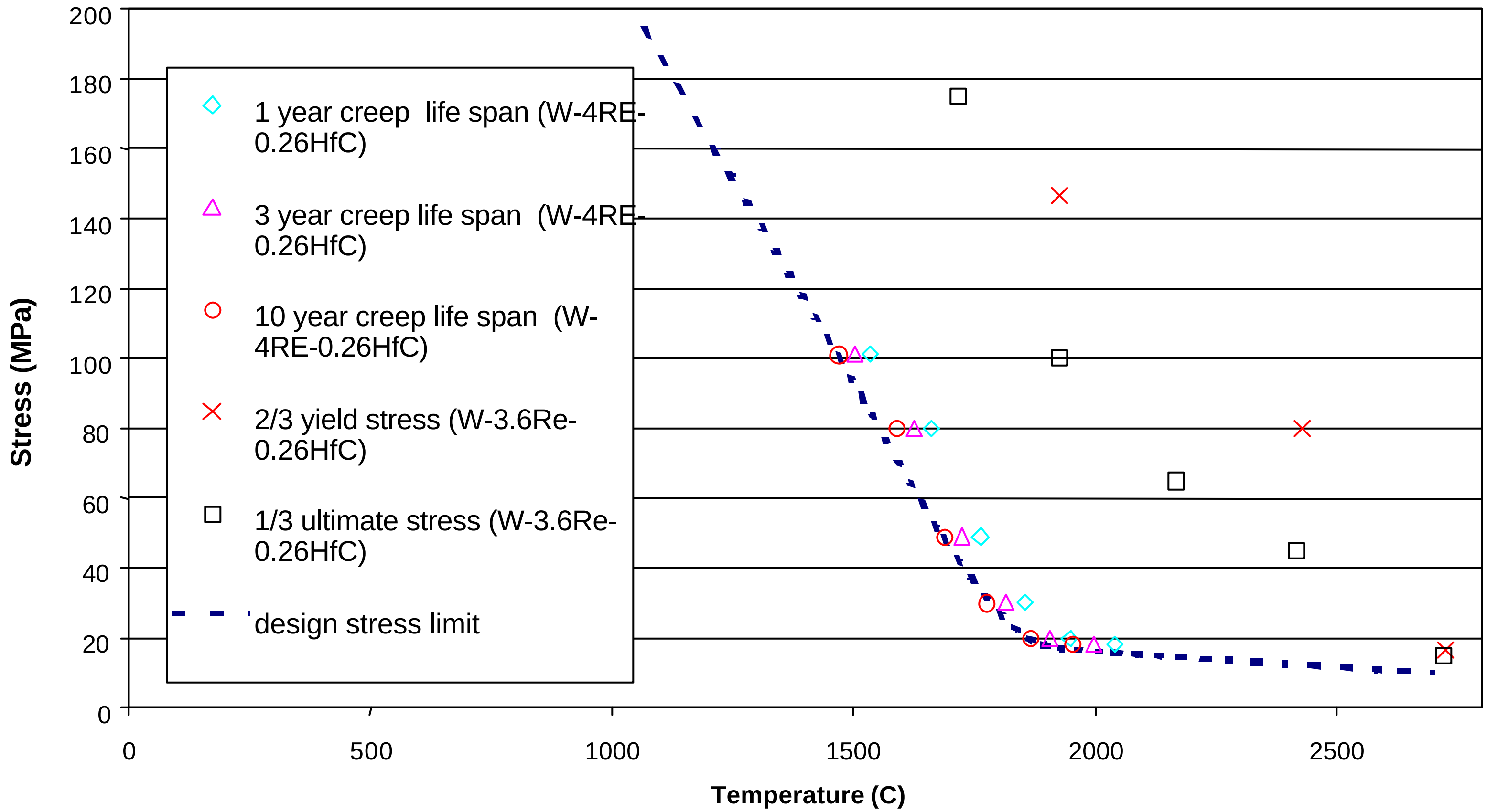
References: Vandervoort, "Creep Behavior of W-5Re", Met. Trans., 1 (1970), p. 857-864;
Shin, "High Temperature Properties of Particle Strengthened W-5Re", JOM August 1990, p. 12-15;
Taylor, "Tensile Properties of W-3%Re in a Vacuum", J. of the Less Common Metals, 7 (1964), p. 27

LARSON-MILLER BASED CREEP-RUPTURE OF W-26Re and W-24Re
(Arc-Melted, Recrystallized and Annealed)



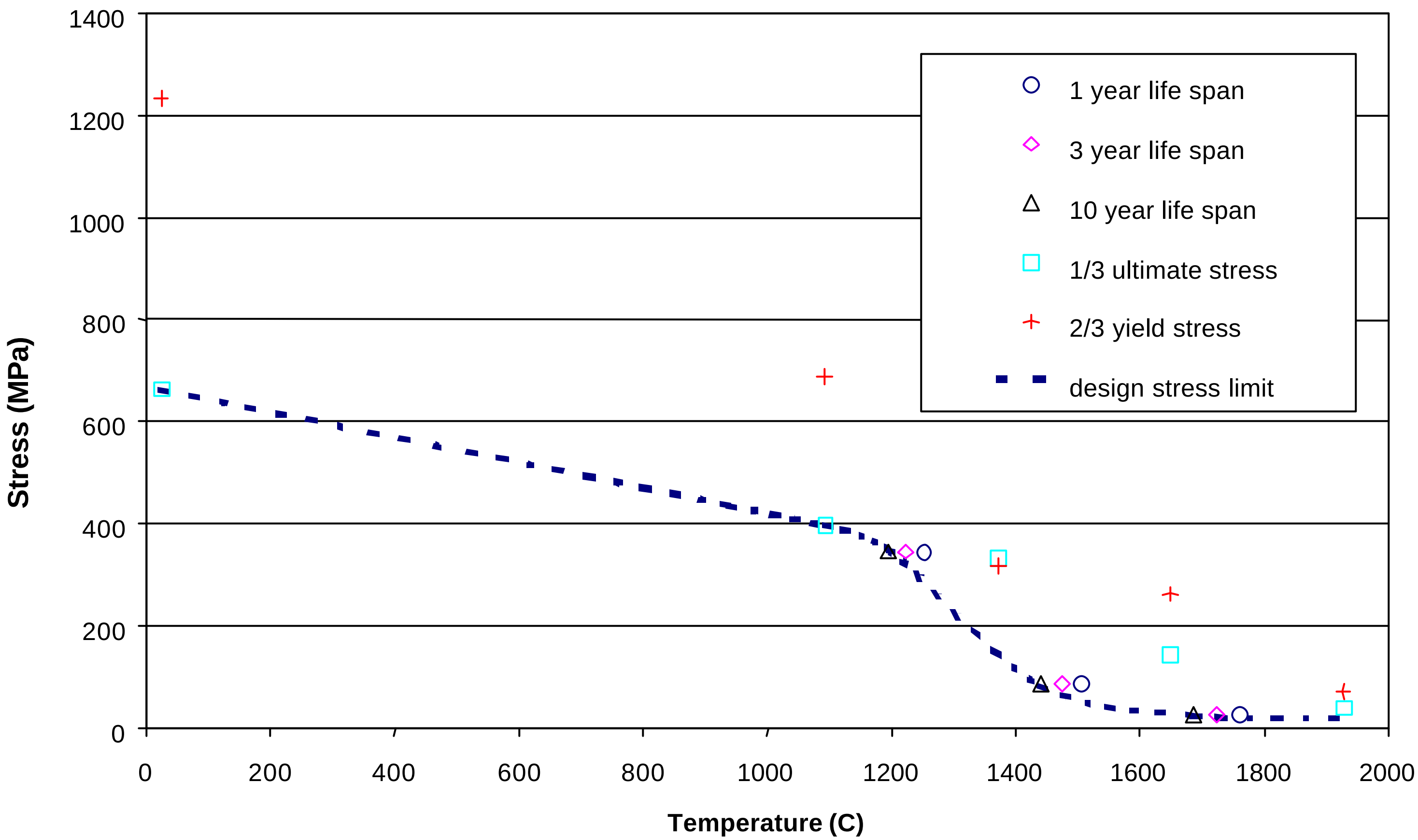
References: Klopp, Refractory Metals and Alloys IV-Research and Development, Gordon-Breach, New York, 1967, p. 557; Shin, "High Temperature Properties of Particle Strengthened W-5Re", JOM August 1990, p. 12-15

LARSON-MILLER BASED CREEP-RUPTURE OF W-4Re-0.26HfC and W-3.6Re-0.26HfC
(Arc-Melted, Recrystallized)



References: Shin, "High Temperature Properties of Particle Strengthened W-5Re", JOM August 1990, p. 12-15

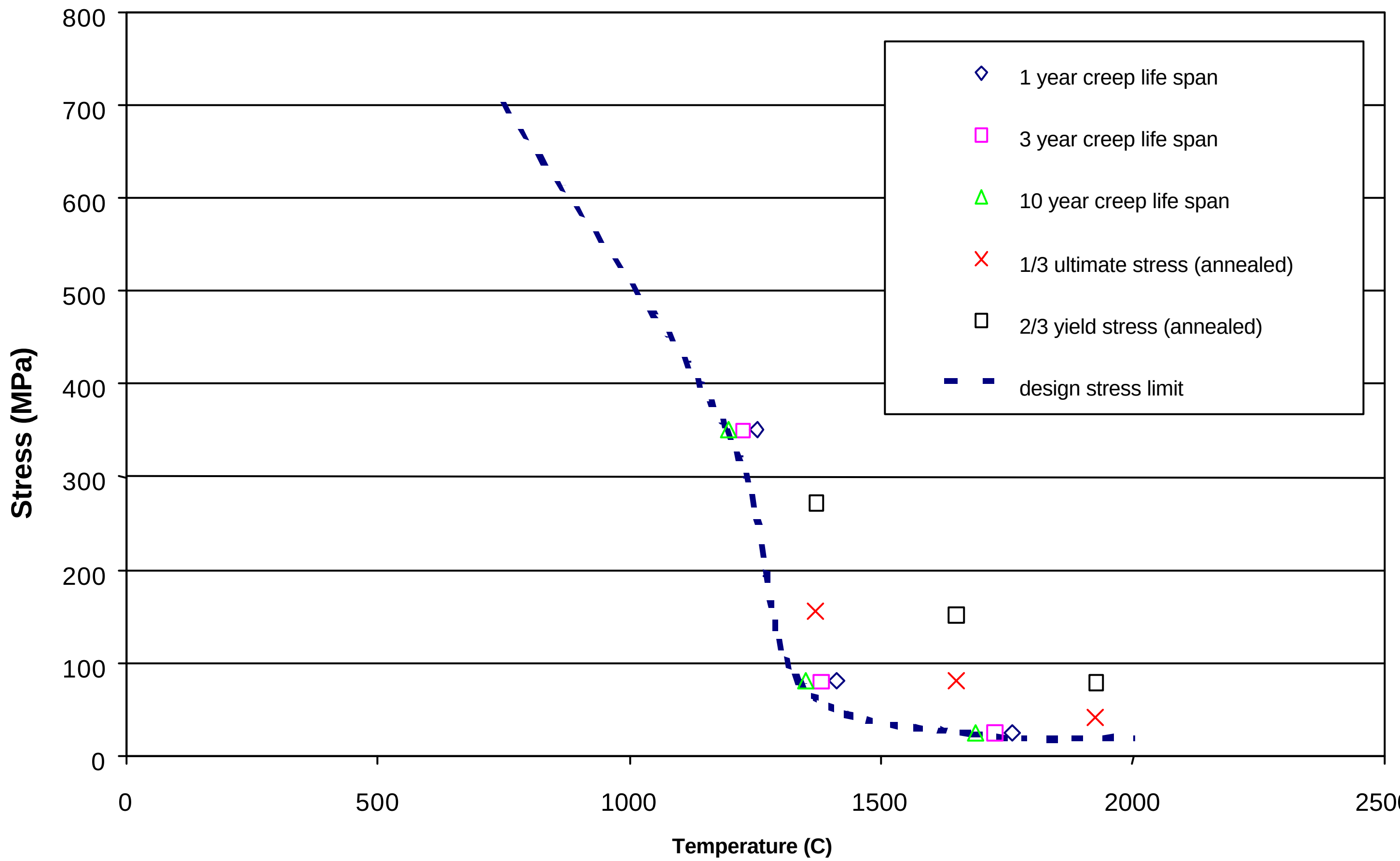
LARSON-MILLER BASED CREEP-RUPTURE OF W-23.4Re-0.27HfC
(Arc-Melted, Swaged)



References: Klopp, "Mechanical Properties of a Tungsten 23.4%Re-0.27%HfC Alloy", J. of the Less Common Metals, 24 (1971) p. 427-442; Shin, "High Temperature Properties of Particle Strengthened W-5Re", JOM August 1990, p. 12-15

LARSON-MILLER BASED CREEP-RUPTURE OF W-23.4Re-0.27HfC

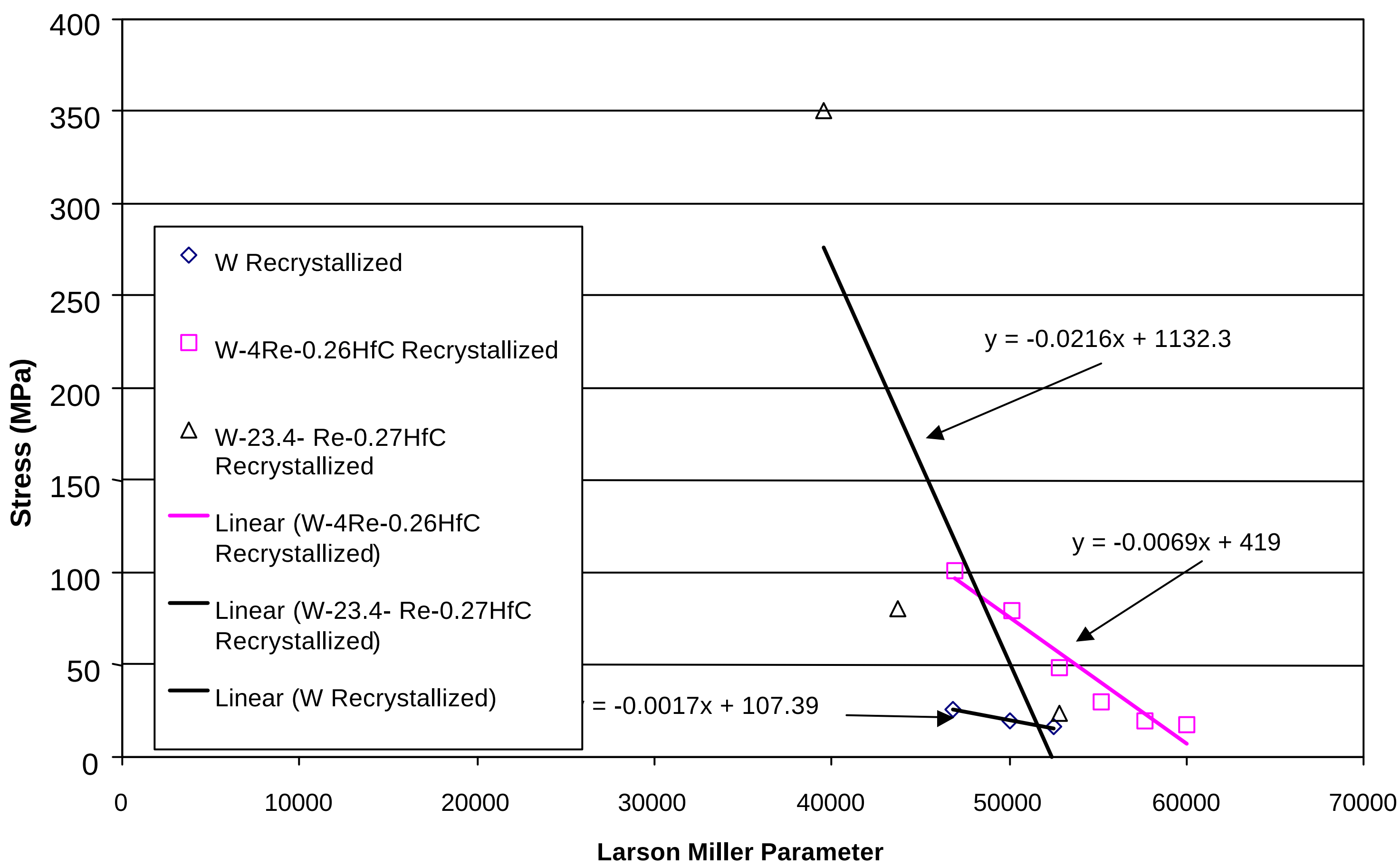
(Arc-Melted, Recrystallized)



References: Witzke, “Mechanical Properties of a Tungsten 23.4%Re-0.27% HfC Alloy”, J. of the Less Common Metals, 24 (1971), p. 427-442

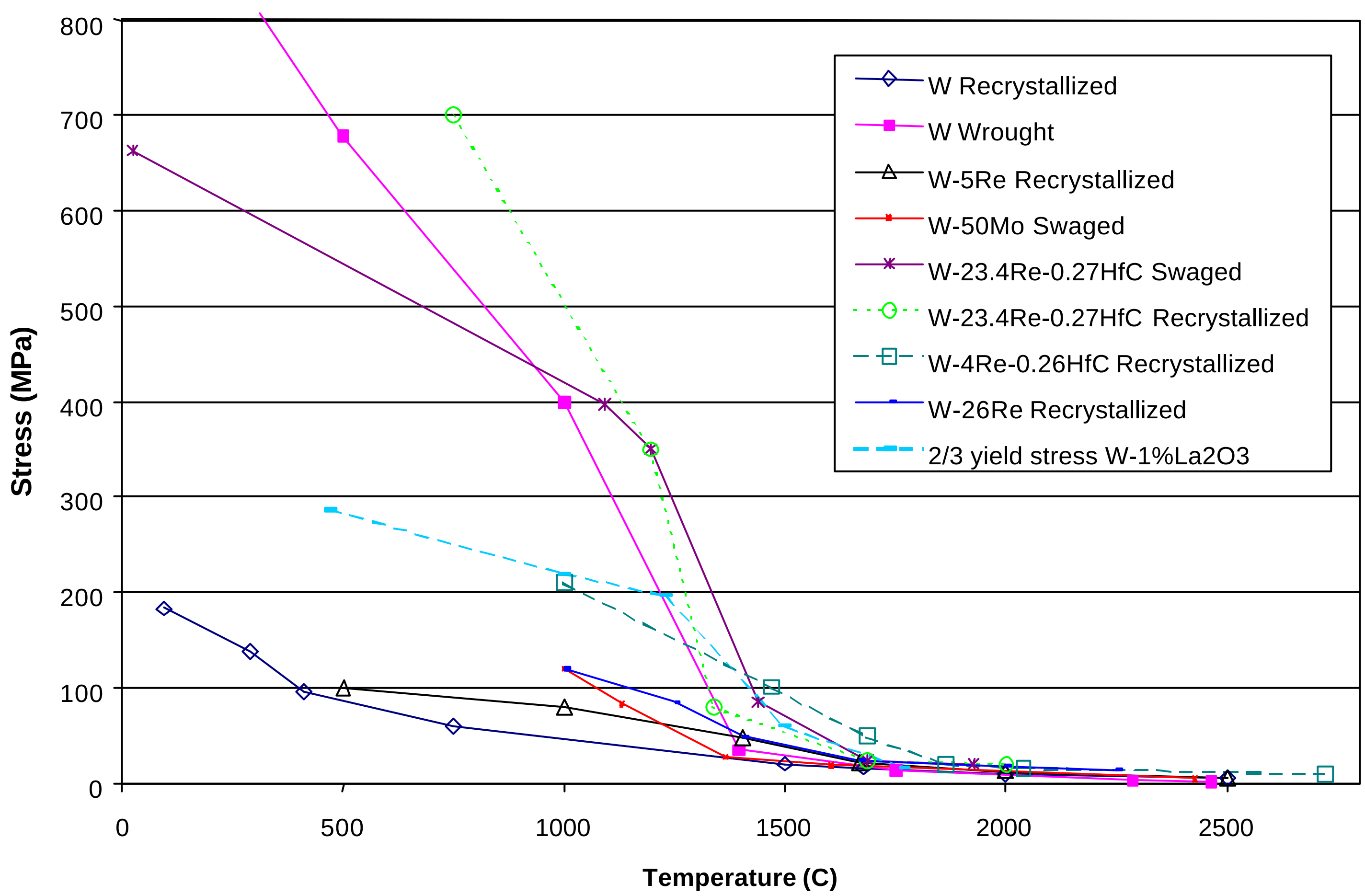
LARSON-MILLER MASTER PLOT FOR Pure W, W-4Re-0.26HfC, W-23.4Re-0.27HfC

(All Recrystallized)

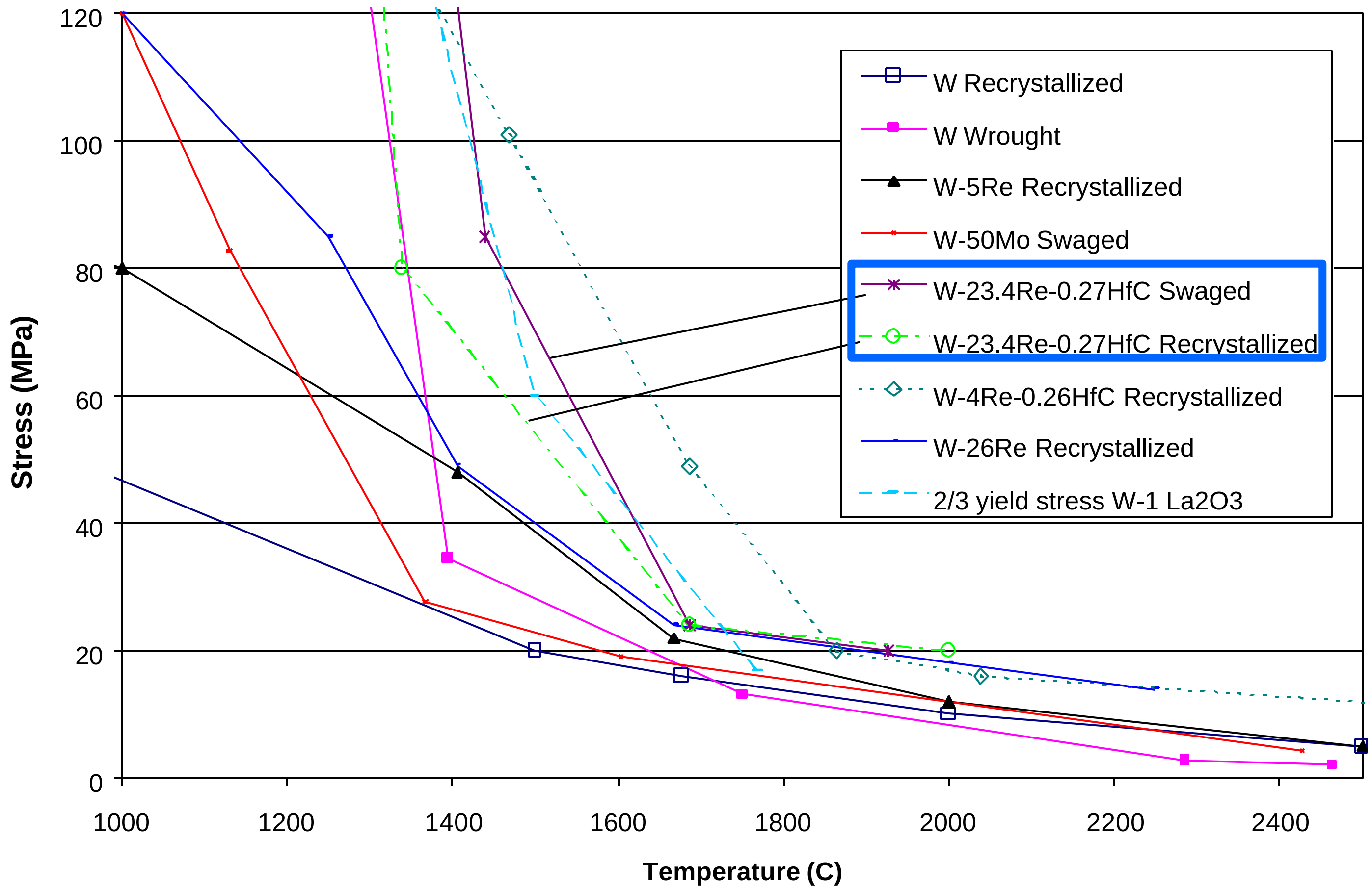


Comparison of Design Stress Limits of W-Alloys

(All Recrystallized)



Comparison of High Temperature Design Stress Limits of W-Alloys



W-23.4Re-0.27HfC

A NEWLY SUGGESTED W-ALLOY

Particle (HfC) strengthening provides W with high temperature strength

High Re content provides substantial low temperature ductility to W

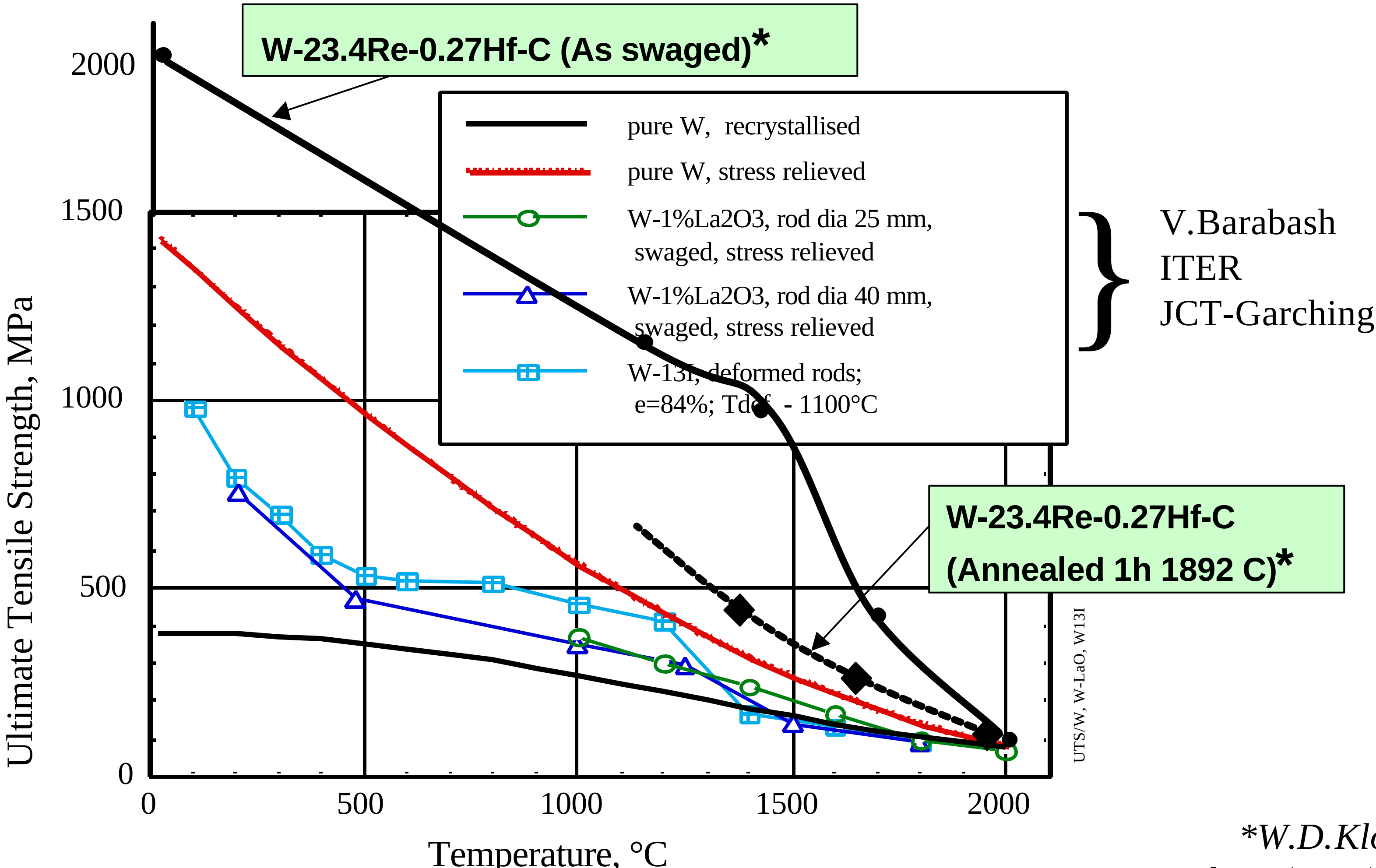
COMBINATION OF THESE

- A TUNGSTEN-Alloy Which Exhibits Good High Temperature Strength and Excellent Low Temperature Ductility
  - *At 1650^{o}C the tensile strength is 432 MPa which is double the strength of W-24Re alloys (194 MPa).*

This Ductile **W-23.4Re-0.27HfC** Alloy has been consolidated by Arc-Melting and Fabricated into Sheets and Rods

W-23.4Re-0.27HfC

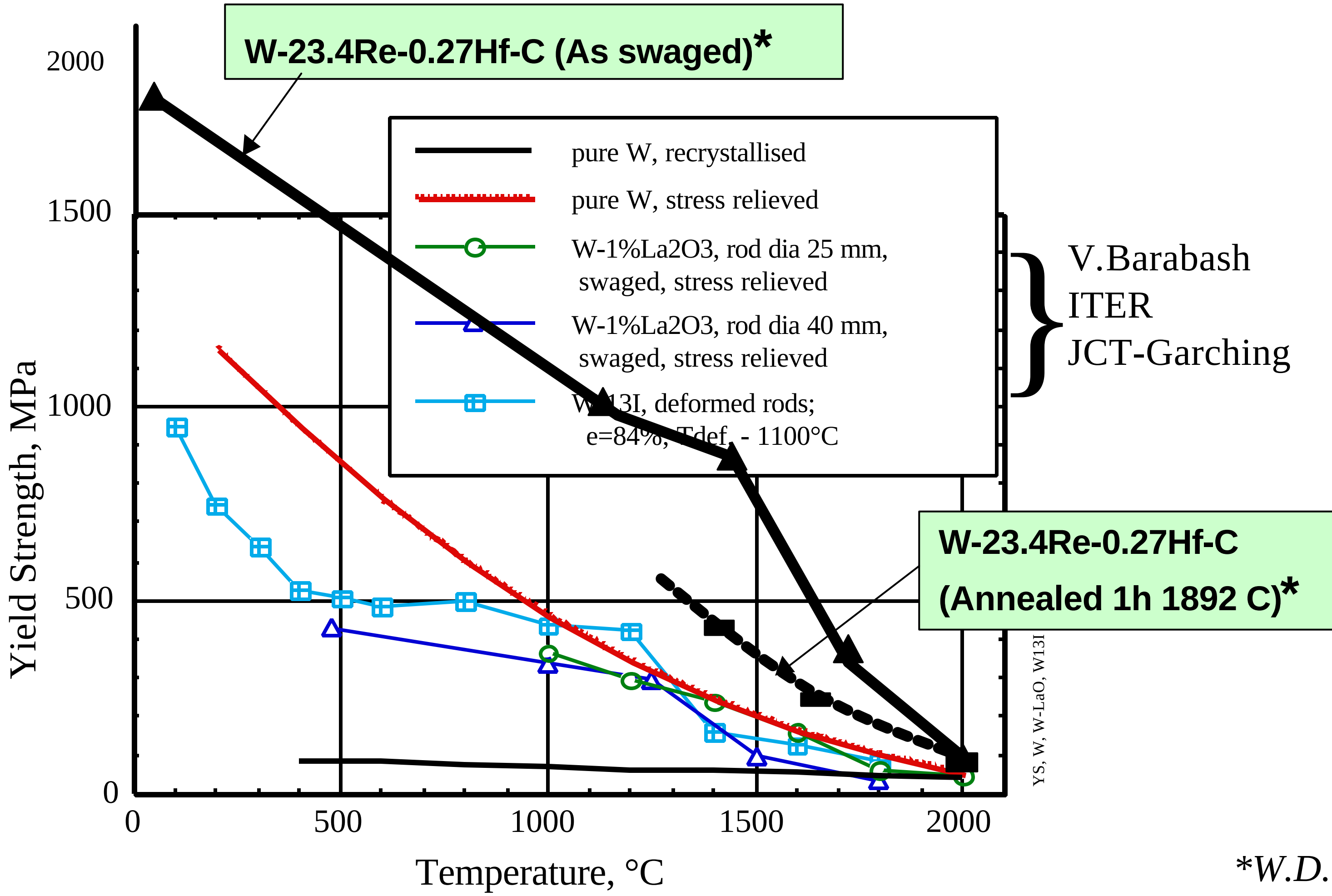
ULTIMATE STRENGTH
(As-Swaged and Annealed)



**W.D.Klopp,*
J. Less-Common Metals,24(1971)427

W-23.4Re-0.27HfC

TENSILE STRENGTH
(As-Swaged and Annealed)

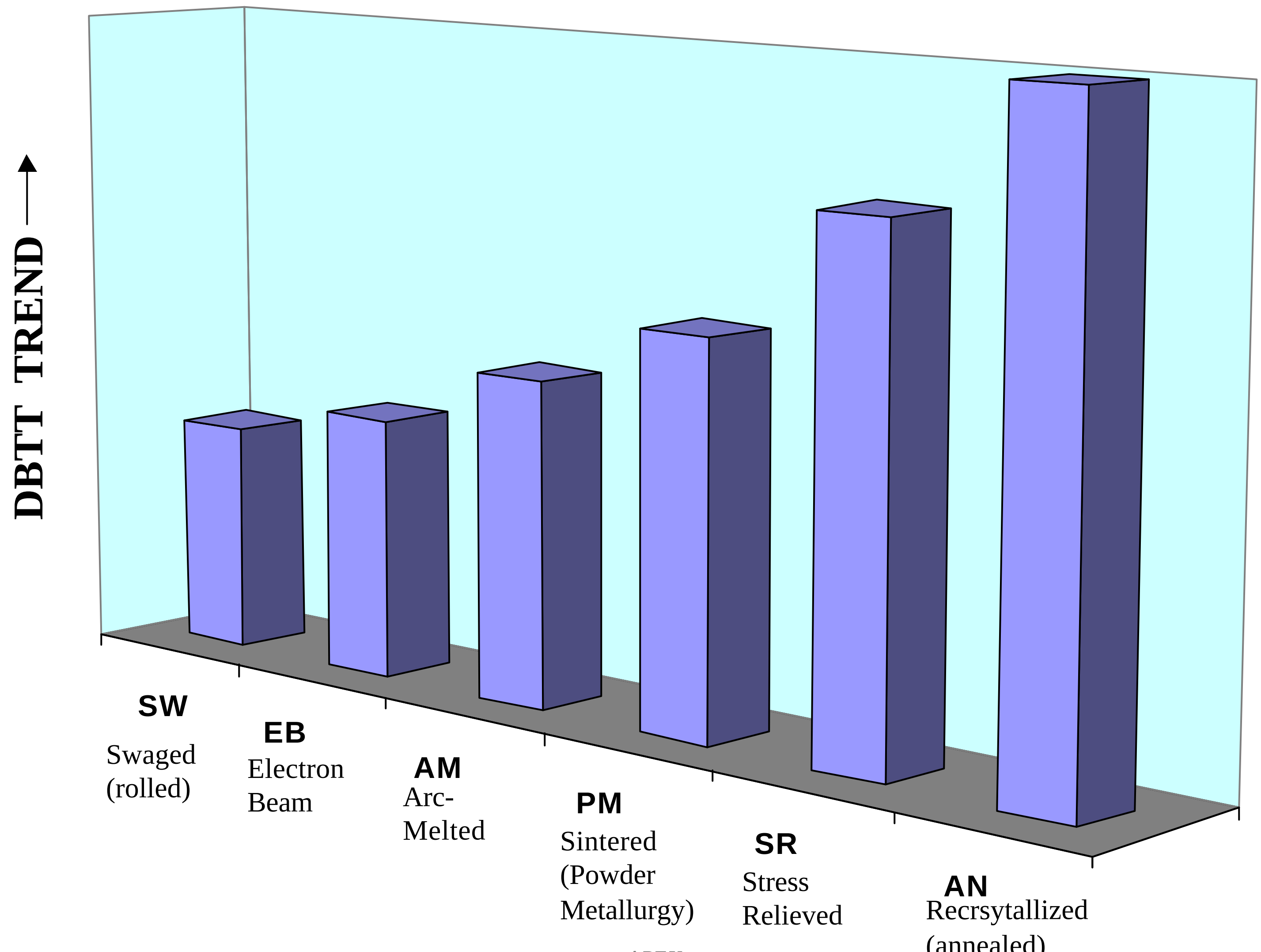


*W.D.Klopp,
J. Less-Common Metals,24(1971)427

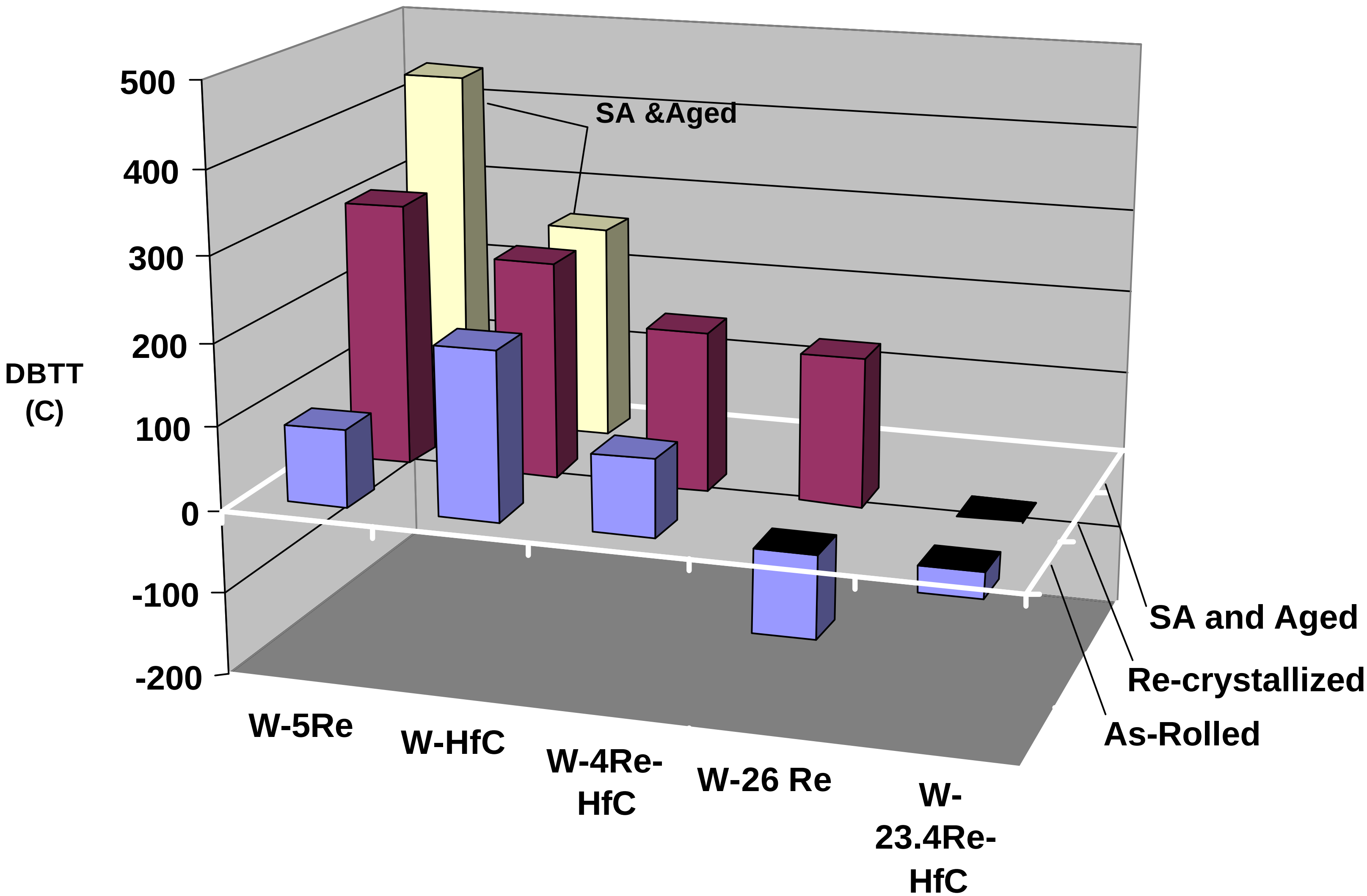
DUCTILE-TO-BRITTLE-TRANSITION TEMPERATURE (DBTT)

- <u>DBTT DEPENDS ON:</u>
  - Production History (thermomechanical treatment)
  - Alloying Elements
  - Neutron Irradiation
  - Irradiation Temperature

Effect Of Fabrication on the DBTT Of Refractory Metals



EFFECT OF ALLOYING ON THE DBTT OF W-ALLOYS



Effect of Neutron Irradiation on DBTT of W

- Only a few experimental W-data are available
- More work done on Mo-Alloys and TZM
  - A phenomenological approach based on Mo-data is presented
  - The Phenomenological Model is applied to W
- The effect of High Temperature Neutron Irradiation on the DBTT for W is estimated based on the Model.

PHENOMENOLOGICAL DBTT-MODEL

- Neutron irradiation increases DBTT because the resistance to dislocation motion increases (neutron produced depleted zones).

- The shear stress (s_i *friction stress*) necessary to move the dislocations is the sum of long-range (s_{LR}) and short range (s_s)stresses:

$$\boxed{s_i = s_{LR} + s_s}$$

- The increase in long range stress is proportional to $N^{-1/2}$ (N: number density of depleted zones), but the short range stress is proportional to $N^{+1/2}$:

$$\boxed{s_s = s_s^o \left\{ 1 - \left(\frac{T}{T_c} \right)^{2/3} \right\}^{3/2}}$$

T_c is the characteristic temperature at which the depleted zones are annealed out (about 0.44 T_m)

PHENOMENOLOGICAL DBTT-MODEL (cont.)

$$\boxed{s_s^o = \left[\frac{U_o}{4\left(2/3\right)^{1/2}}\right]^{3/2} \frac{1}{b^2 G^{1/2}} \frac{N^{1/2}}{r}}$$

Were:

U_o: cutting energy for a dislocation; b: burgers vector; G:shear modulus; r: radius of obstacle to dislocation motion; N: number density of depleted zones.

- Saturation of Radiation Hardening (in the absence of destruction mechanism) is based on the time rate of change of fast-neutron induced clusters:

$$\boxed{\frac{dN}{dt} = a\Sigma_s\Phi\left(1 - vN\right)}$$

Were:

α: number of cluster zones per neutron (~1); Σ_s macroscopic scattering cross-section; v: capture volume around a depleted zone; Φ: neutron fluence.

PHENOMENOLOGICAL DBTT-MODEL (cont.)

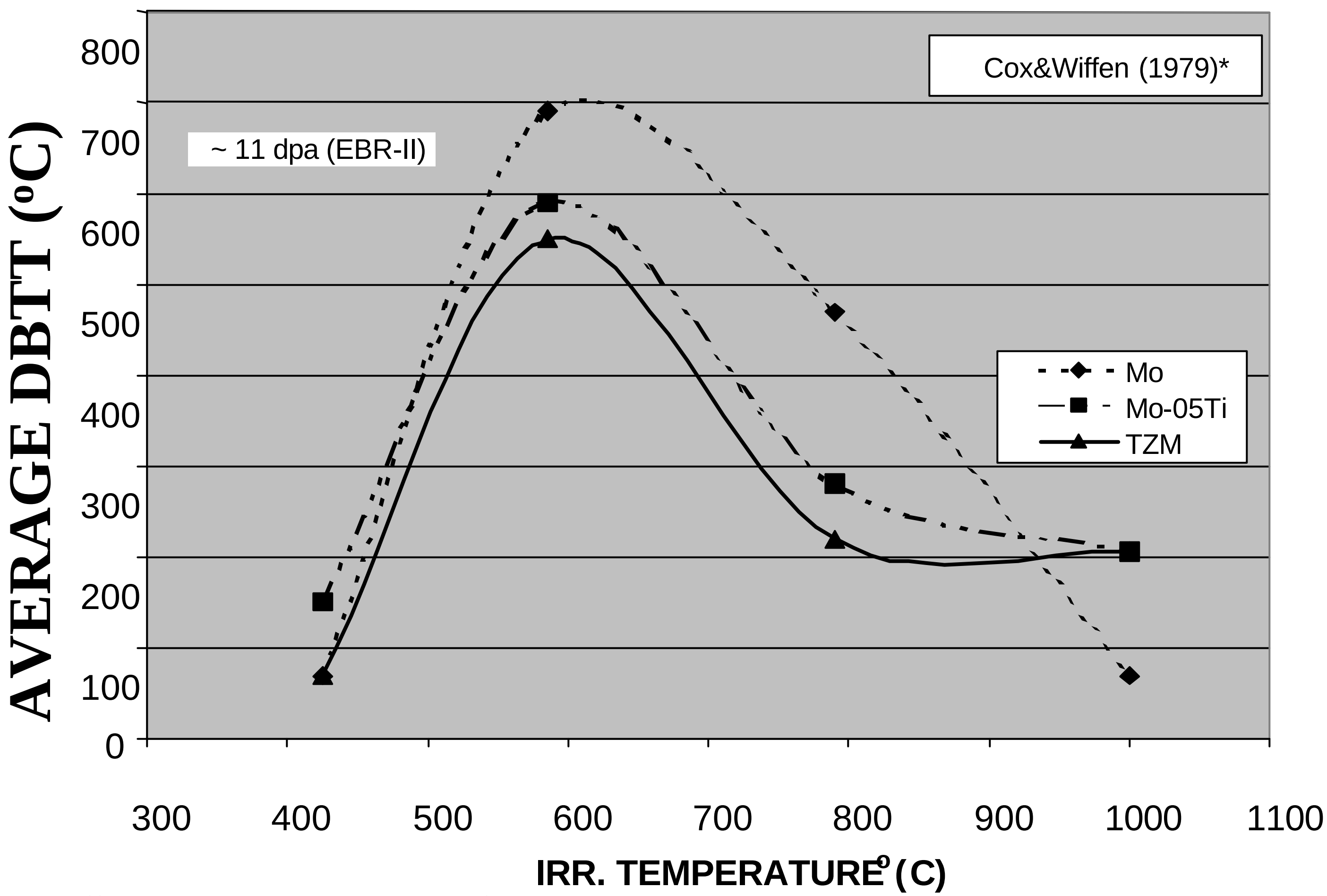
- In the absence of destruction mechanisms:

$$\boxed{s_s \propto [1 - \exp(-a v \Sigma_s \Phi t)]^{1/2}}$$

- Thermal annealing of depleted zones at high temperatures significantly affects the zones number density at a decay time (τ) proportional to τ_o

$$\boxed{N(T,t) = \left[\frac{1}{v + \frac{1}{a\Sigma\Phi t(T)}}\right]\left[1 - \exp\left\{-(a\Sigma\Phi v + \frac{1}{t(T)})\right\}t\right]}$$

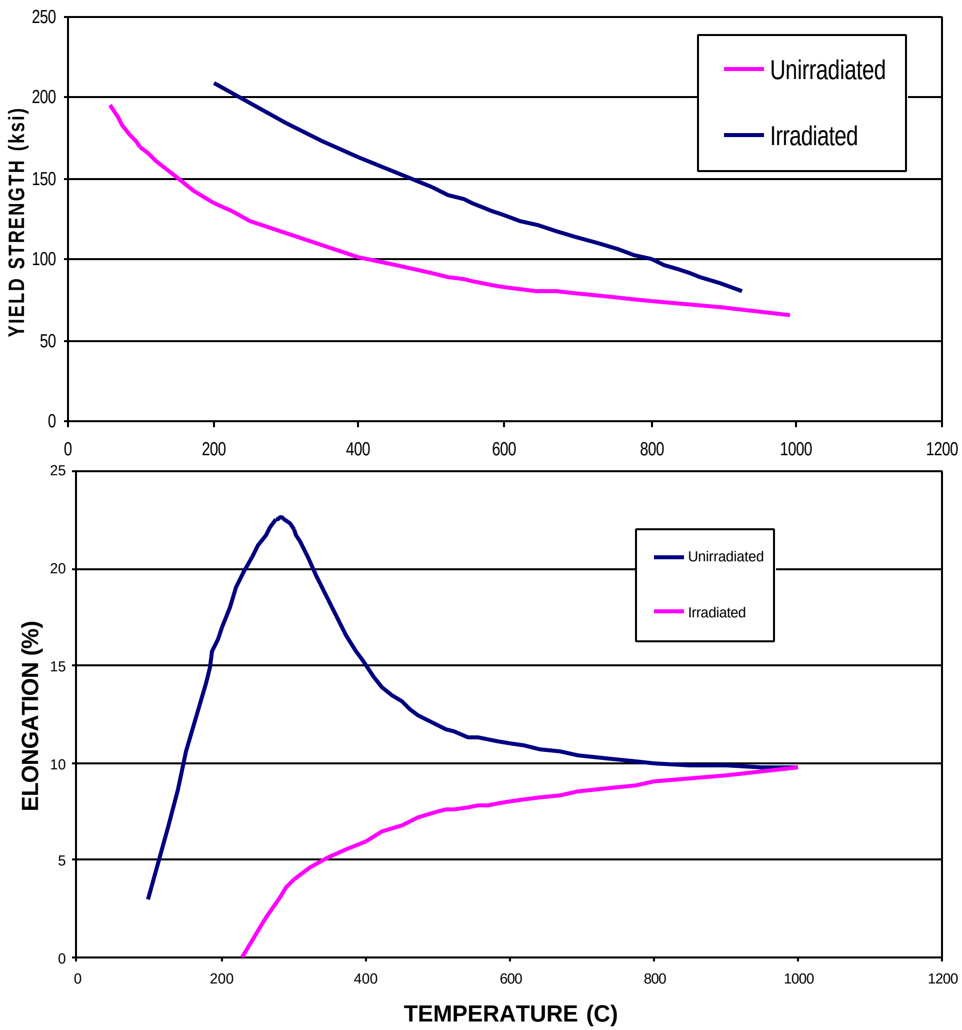
IRRADIATED Mo-DATA



*B. Cox, F. Wiffen "The Ductility in Bending of Molybdenum Alloys Irradiated Between 425 and 1000°C," *J. Nucl. Mat.* 85&86(1979)901-905.

IRRADIATED W-DATA

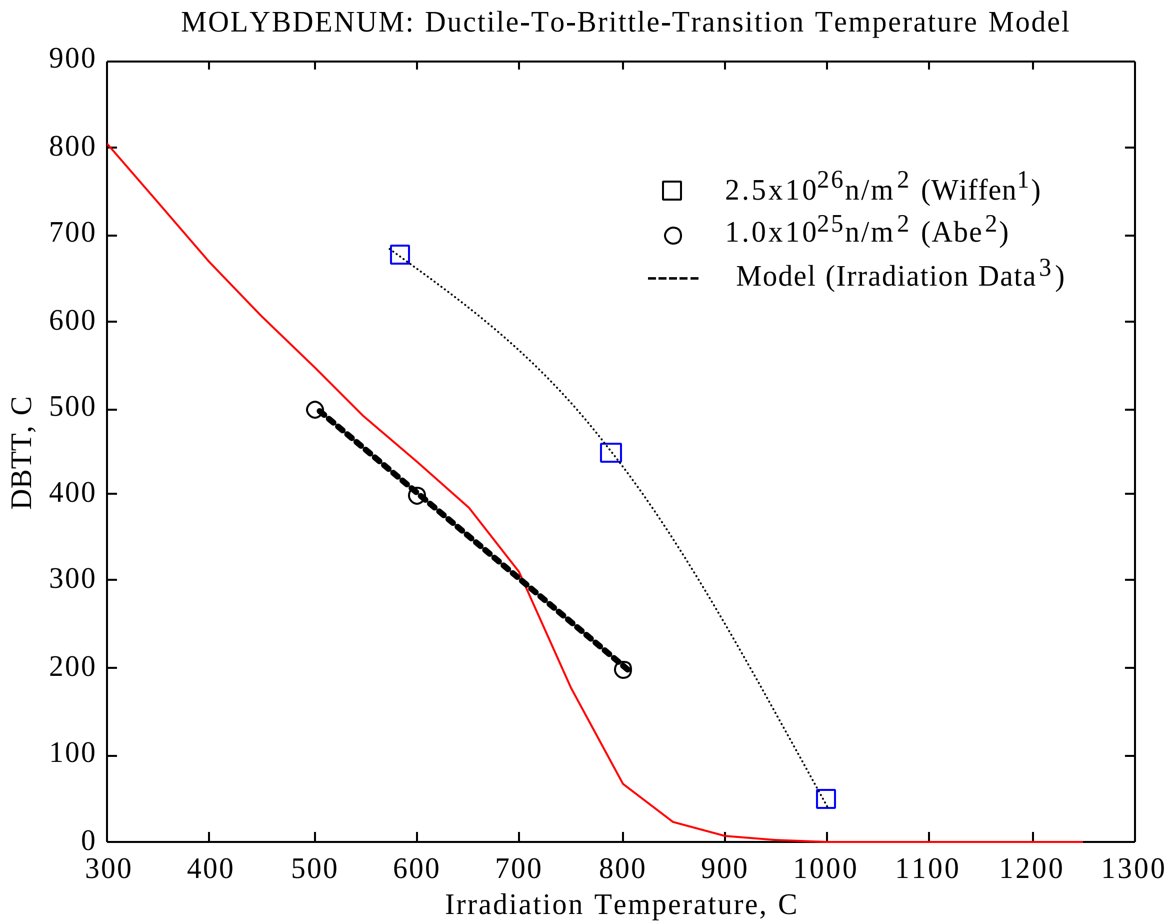
TENSILE PROPERTIES OF TUNGSTEN
AS A FUNCTION OF TEMPERATURE AND IRRADIATION



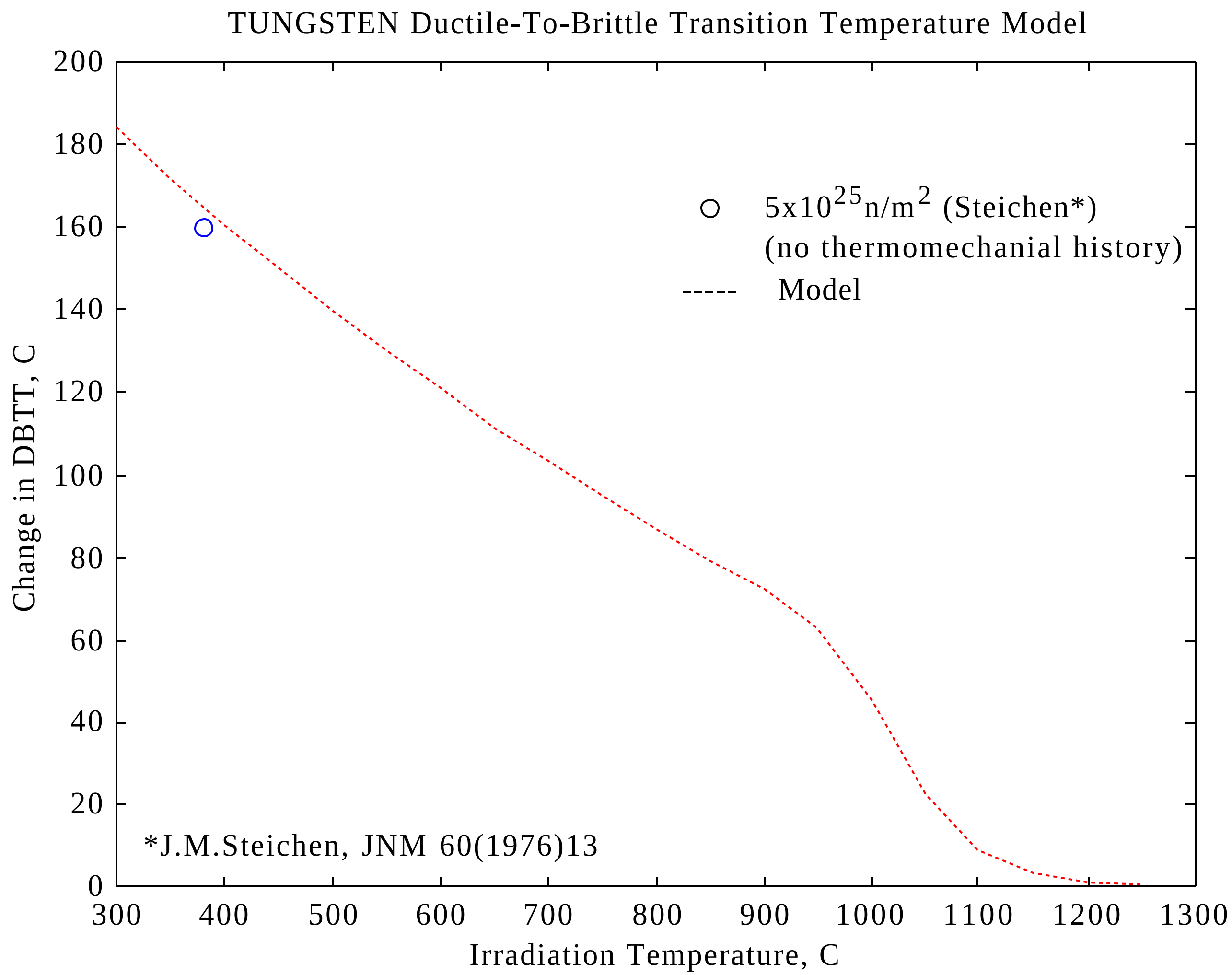
Reference:
Steichen, "Tensile Properties of Neutron Irradiated TZM and Tungsten", Journal of Nuclear Materials, 60 (1976) p. 13-19

PHENOMENOLOGICAL DBTT-MODEL APPLIED TO Mo-DATA

- The model was applied to the Mo neutron irradiated data:

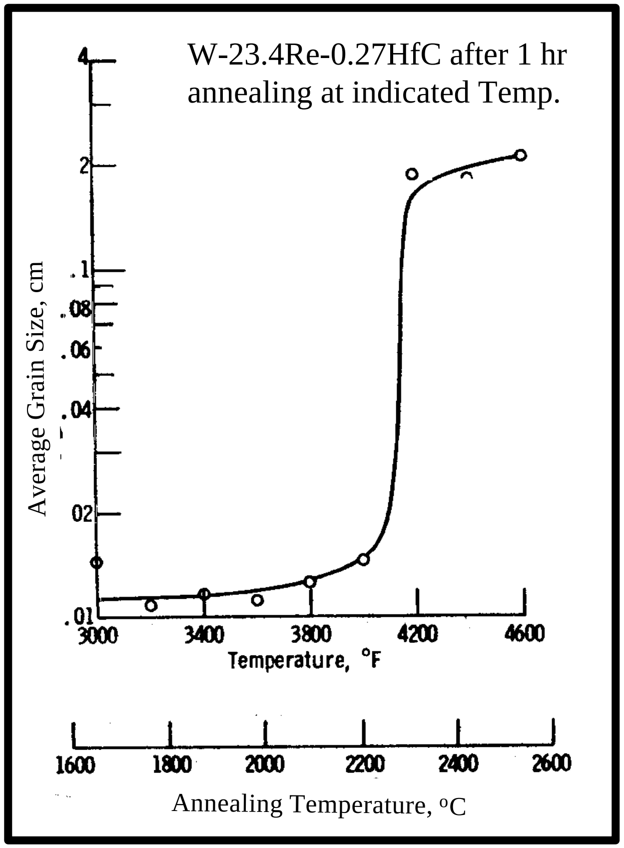


PHENOMENOLOGICAL DBTT-MODEL APPLIED TO W-DATA



RECRYSTALLIZATION TEMPERATURE OF W-ALLOYS

ALLOY	RE-CRYSTALLIZATION TEMPERATURE (°C)
W	1150 - 1350 [1]
W-5Re	>1500 [1]
W-24Re	1593 [2]
W-1%La_2O_3	1200 - 1700 [1]
W-23.4Re-0.27HfC	1704 (e-beam welded) [3]



[1] I. Smid, et al., J. Nucl. Mater., 258-263(1998)160
[2] W.D.Klopp, Refractory Metals and Alloys IV, Gordon and Breach, NY, 1967, p.557
[3] W.D.Klopp, J. Less-Common Metals,24(1971)427

OXIDATION TEMPERATURE LIMITS BASED ON BOUNDARY LAYER EFFECTS

- Based on experimental data, the impingement rate of O_2 as a function of ppm was estimated for calculating the evaporation rate
  - Due to the BOUNDARY LAYER effect the evaporation rate of W was estimated to be below 1μm at 1 ppm O_2 at 1500^{o}C.

DESIGN WINDOW

- Based on the low DBTT, high re-crystallization temperature, high temperature creep resistance the W-23.4Re-0.27HfC alloys should be considered as a candidate material.
- The Design Stress Limit based on the Tensile Design Limits and the 10 year Creep Limit is:
  - about 250 MPa at 1200^{o}C (primary stress)
- The DBTT at elevated irradiation temperatures (>1000^{o}C) for the W-alloy may be small.
- If the DBTT is shown to be larger than expected, annealing at elevated temperature is an option for the W-23.4Re-0.27HfC based on its high re-crystallization temperature (1703^{o}C).
- Oxidation of W at 1ppm O_2 content limits the evaporation rate to less than 1 μm per year at 1500^{o}C