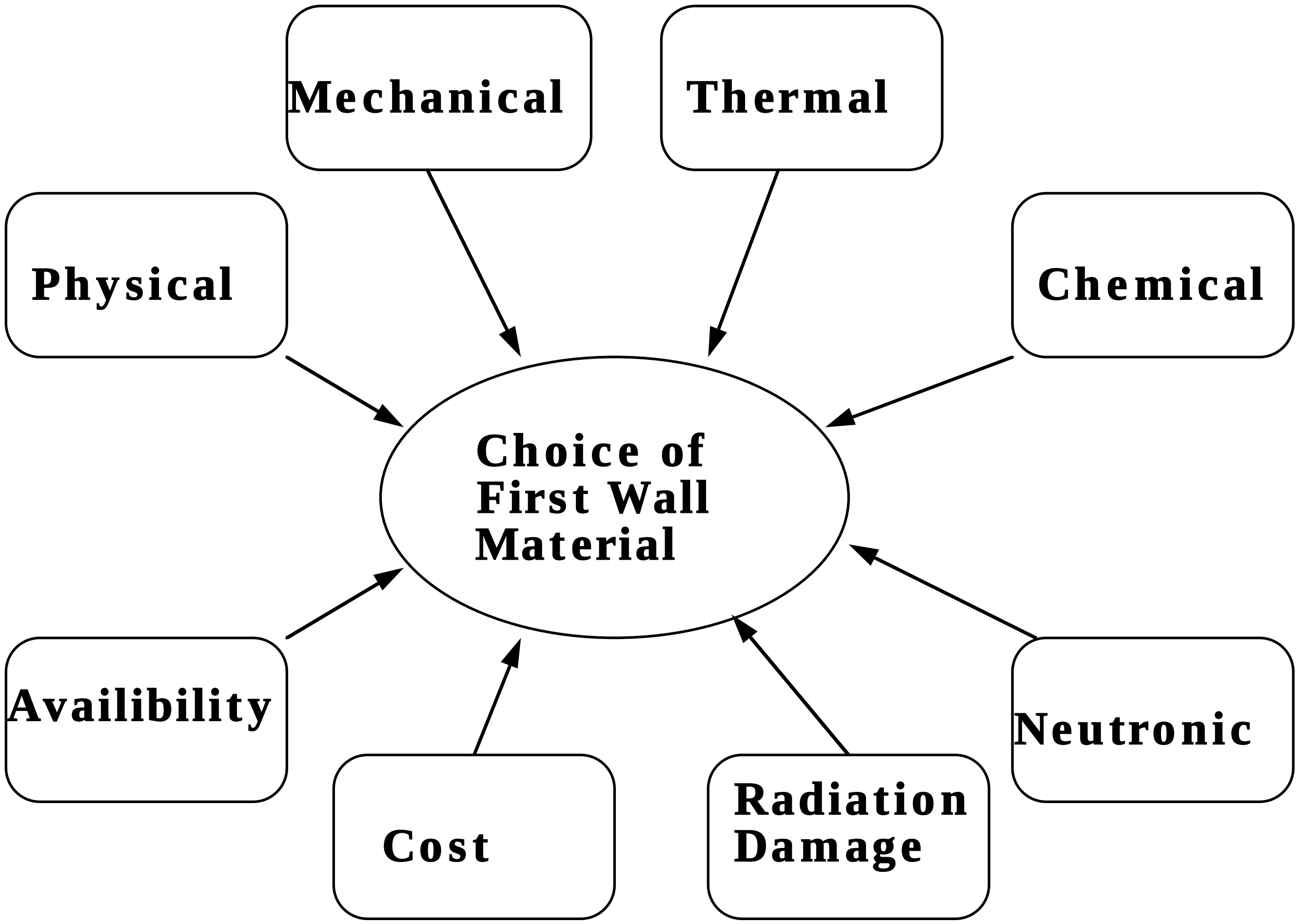
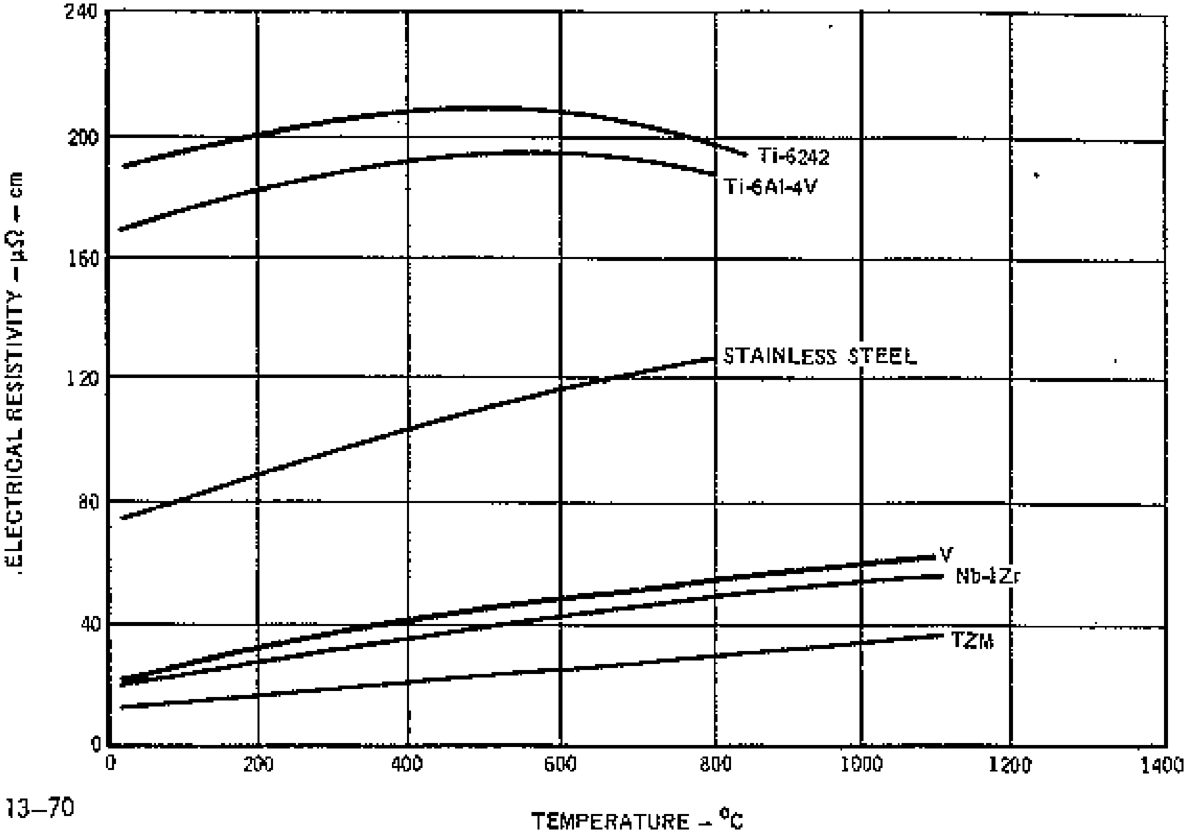

Mechanical
Thermal
Physical
Chemical
Choice of First Wall Material
Availibility
Neutronic
Cost
Radiation Damage

COMPARISON OF ELECTRICAL RESISTIVITY OF SEVERAL CANDIDATE CTR MATERIALS



13–70

Figure 2

ESTIMATED VAPOR PRESSURES OF CANDIDATE FIRST WALL MATERIALS

CANDIDATE FIRST WALL MATERIAL	PROPOSED MAXIMUM OPERATING TEMPERATURE (°C)	ESTIMATED VAPOR PRESSURE (atm)*
ALUMINUM	300	1.34×10^{-47}
TITANIUM	500	2.09×10^{-40}
316 SS	600	1.05×10^{-27}
VANADIUM	800	1.33×10^{-25}
NIOBIUM	1000	7.71×10^{-30}
MOLYBDENUM	1000	9.68×10^{-27}

*Based on the data of Reference 7; extrapolated using linear regression analysis of vapor pressure vs reciprocal temperature data.

Table 3

Thermal Stress

$$\sigma_{th} = \frac{\alpha E}{2k(1-\nu)}\left[w_s t + 0.5 w_n t^2\right]$$

Material Related **Reactor Related**

α = coefficient of thermal expansion
E = Modulus of Elasticity
k = thermal conductivity
ν = Poison Ratio
w_s = surface heat flux
w_n = nuclear heat rate
t = thickness

$$\text{Figure of Merit} = \frac{\sigma_{th}(T)}{\sigma_y(T)}$$

COMPARISON OF MODULUS OF ELASTICITY FOR SEVERAL CANDIDATE CTR MATERIALS

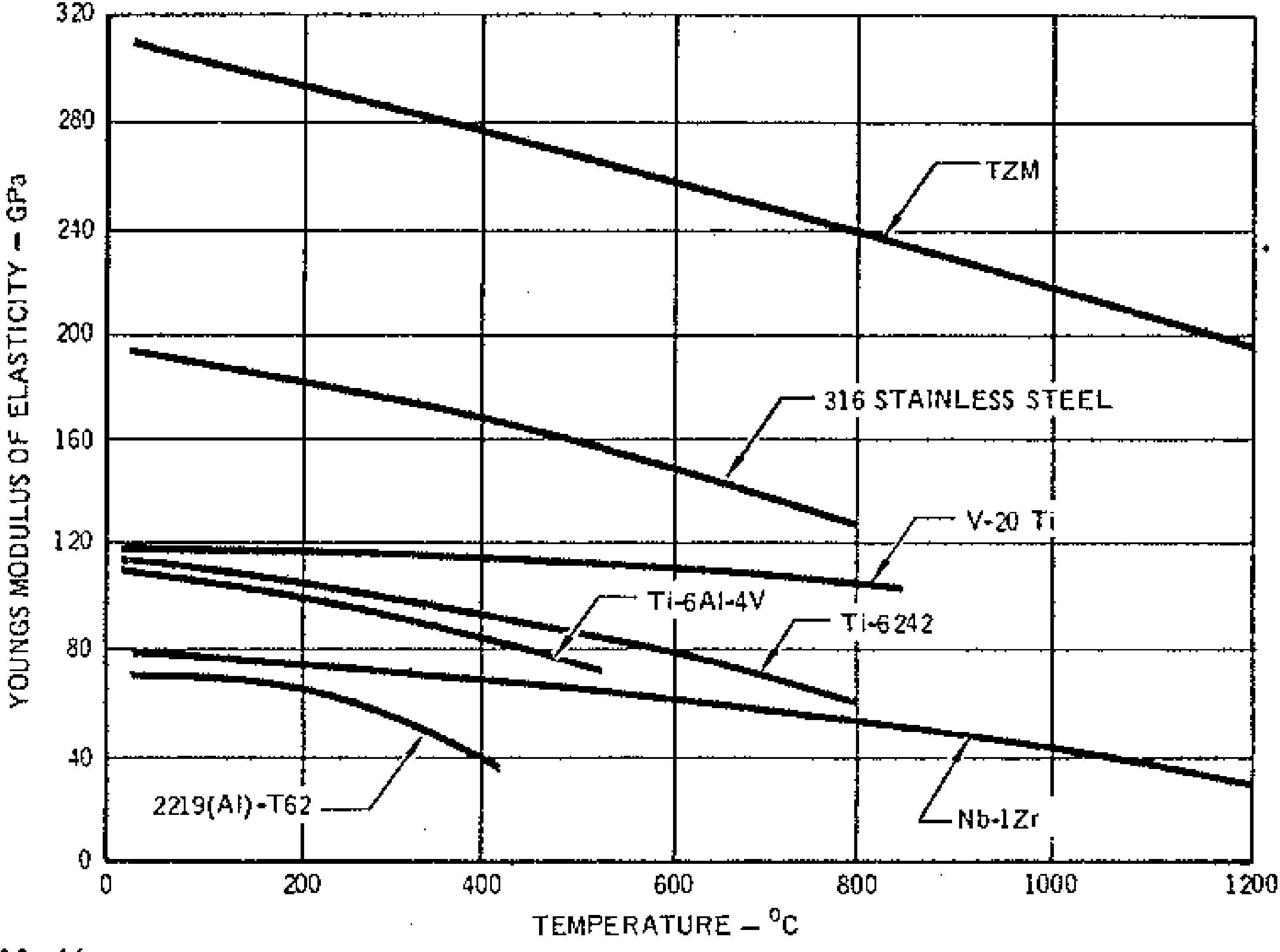
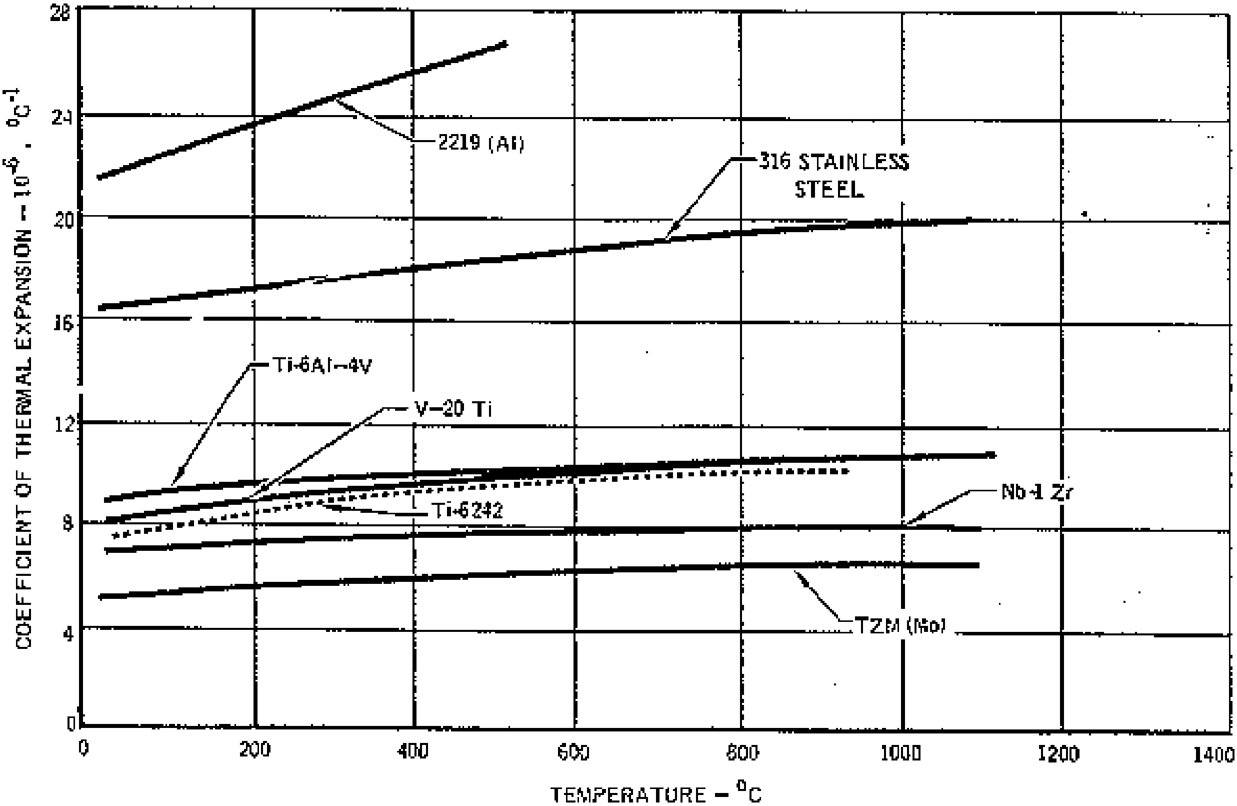


Figure 6

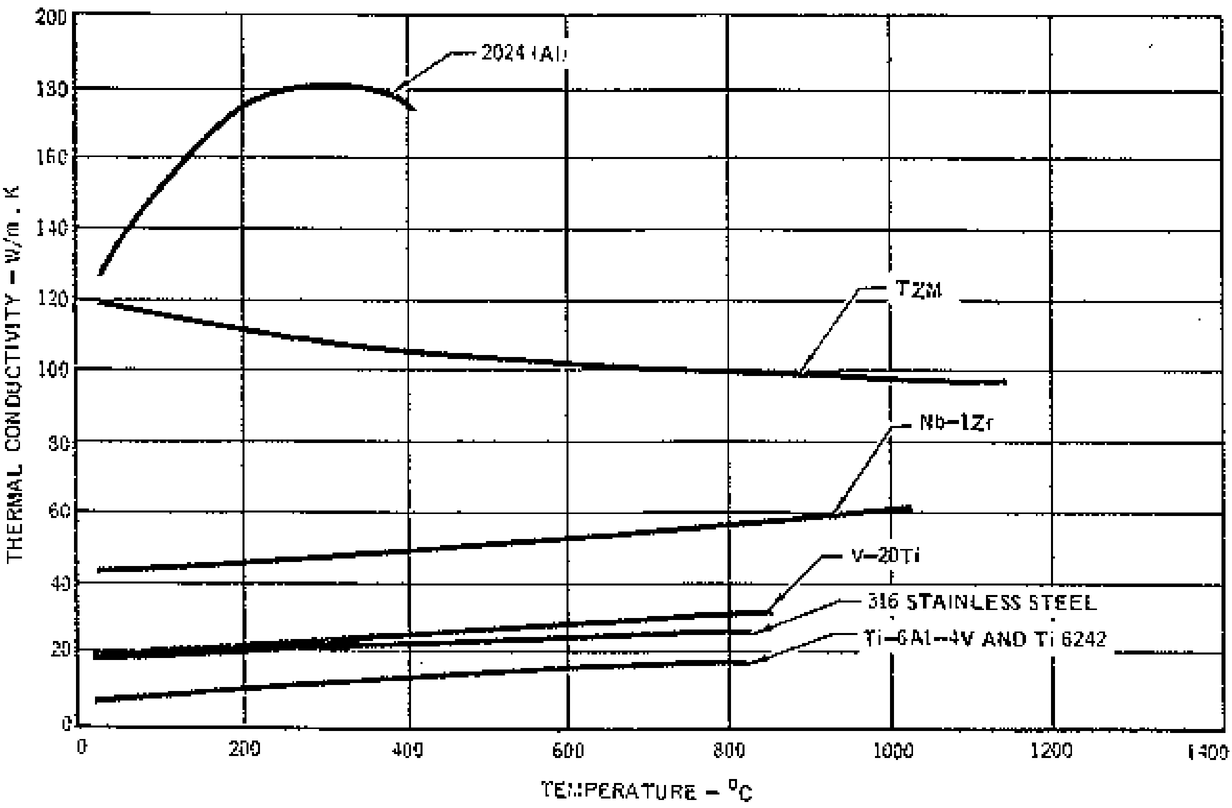
COMPARISON OF THE COEFFICIENT OF THERMAL EXPANSION FOR SEVERAL CANDIDATE CTR MATERIALS



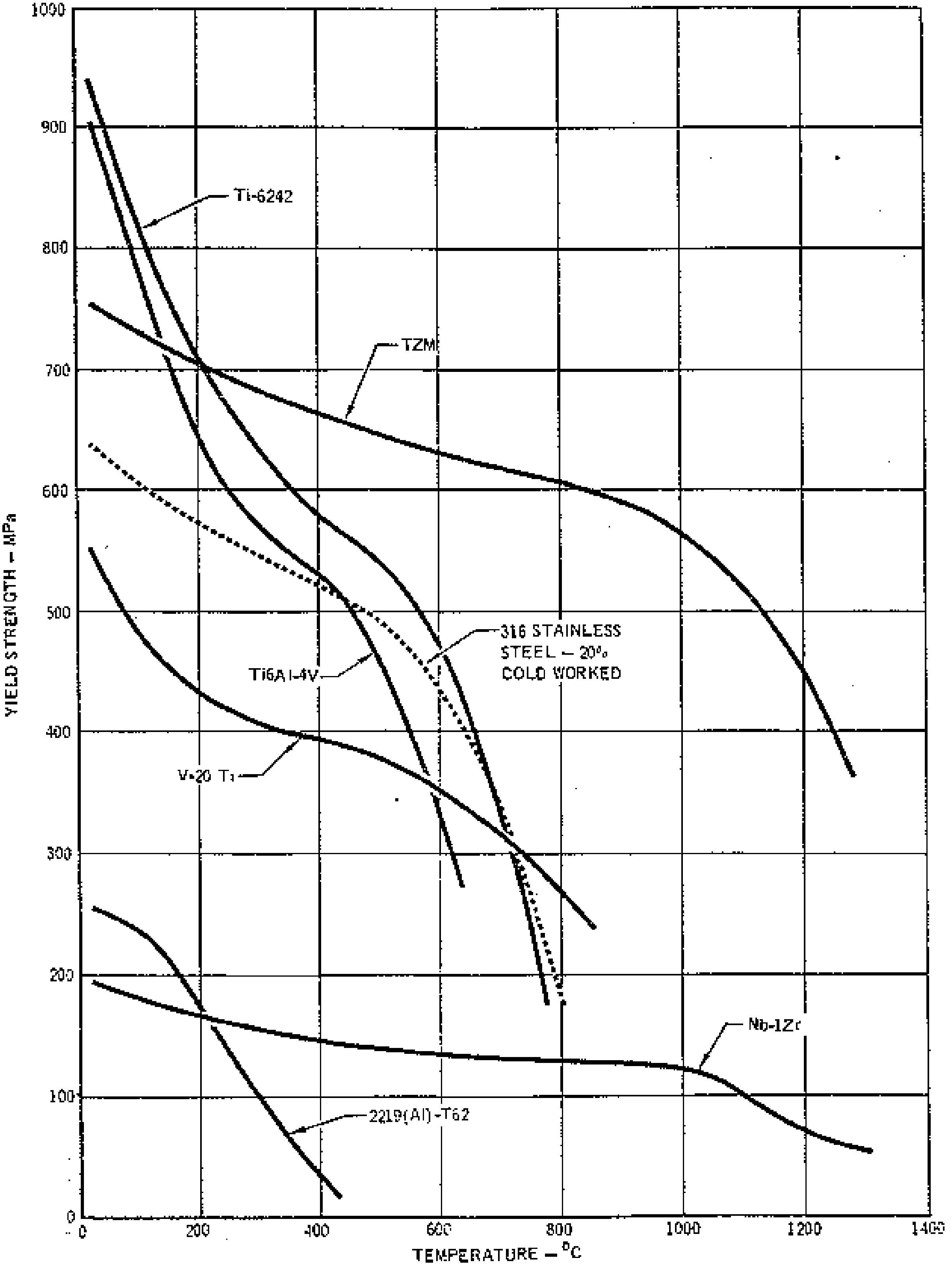
13-187A

Figure 9

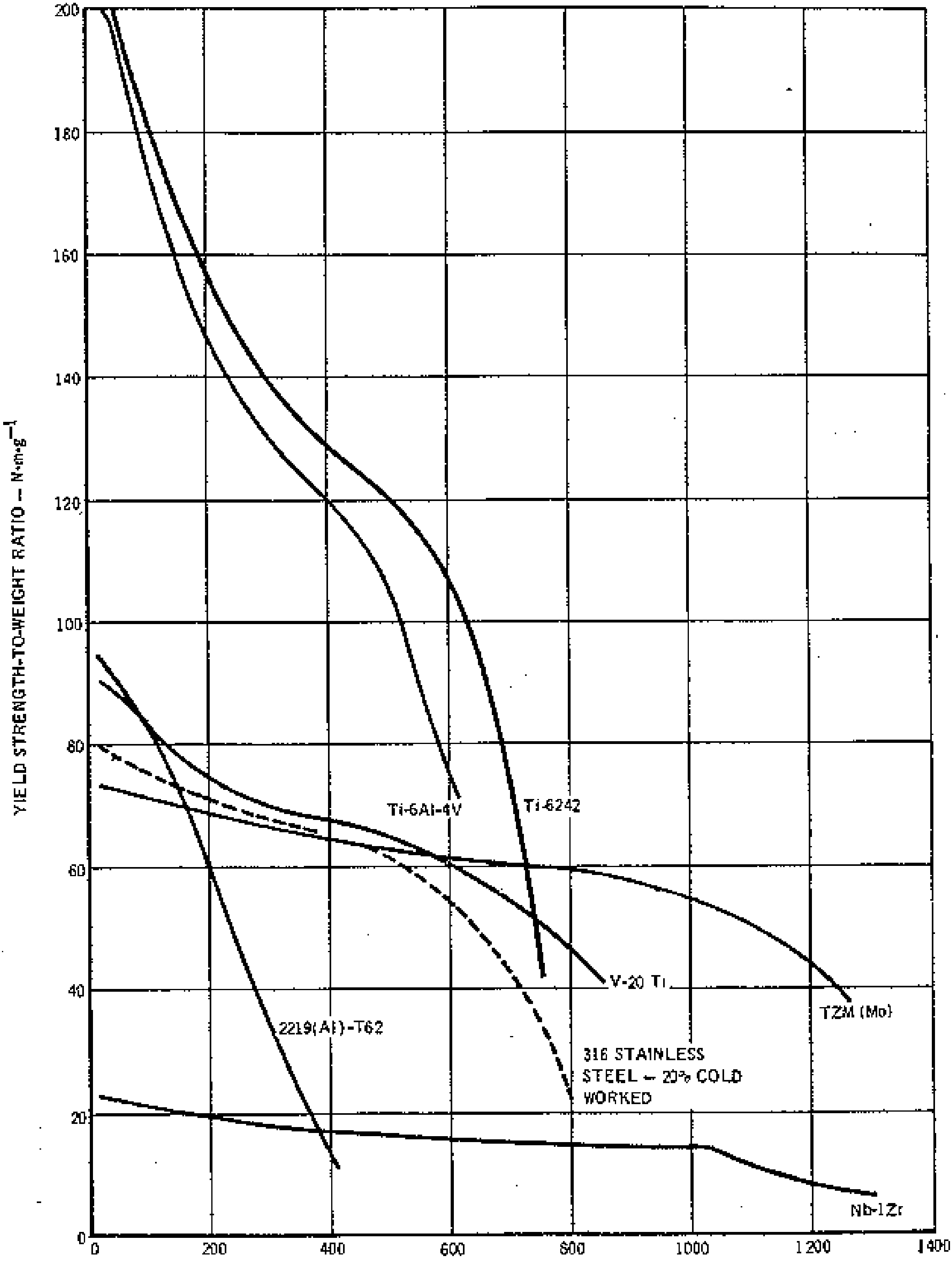
COMPARISON OF THE THERMAL CONDUCTIVITY FOR SEVERAL CANDIDATE CTR MATERIALS



EFFECT OF TEMPERATURE ON THE YIELD STRENGTH OF SEVERAL CANDIDATE CTR MATERIALS



STRENGTH-TO-WEIGHT OF VARIOUS CTR MATERIALS



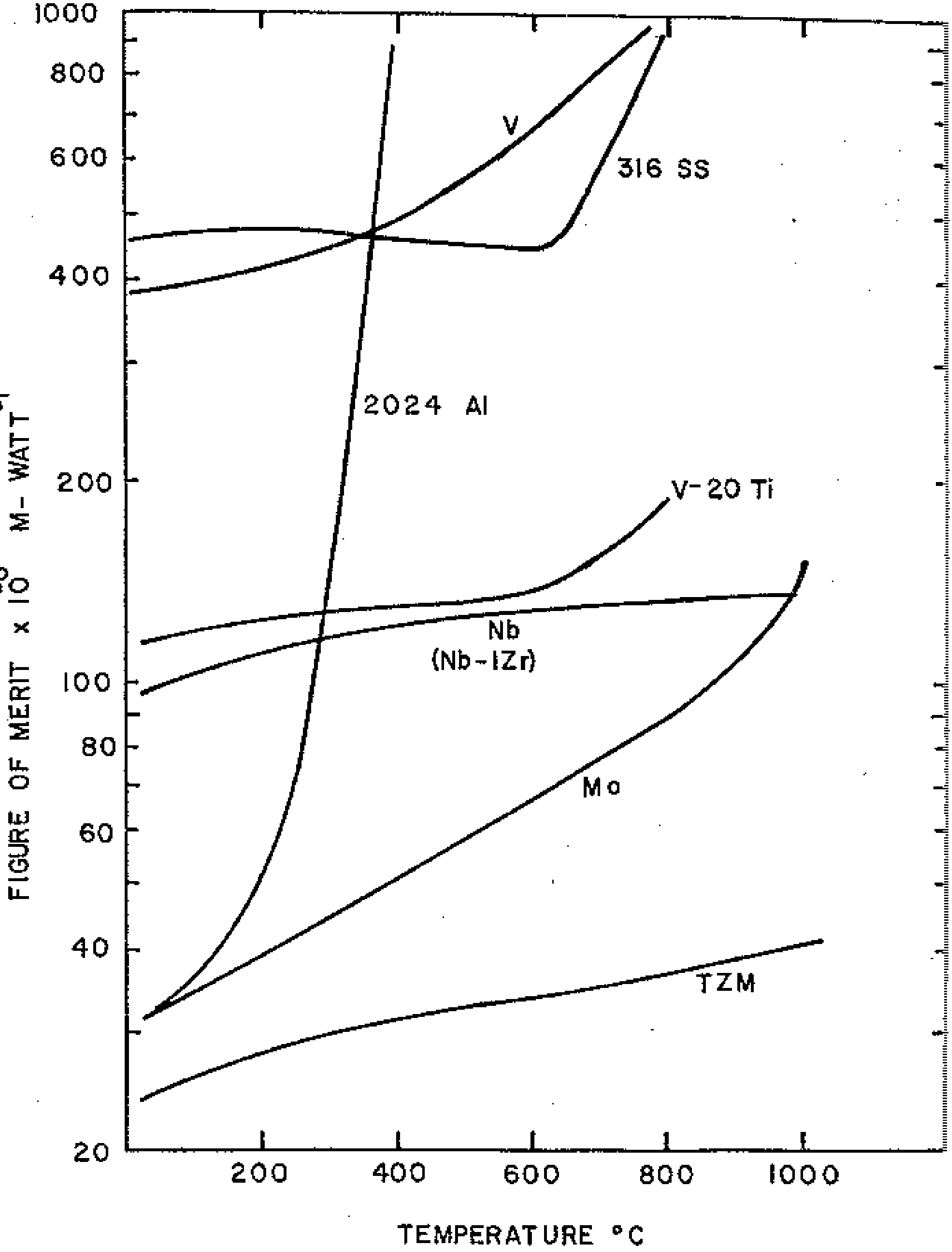
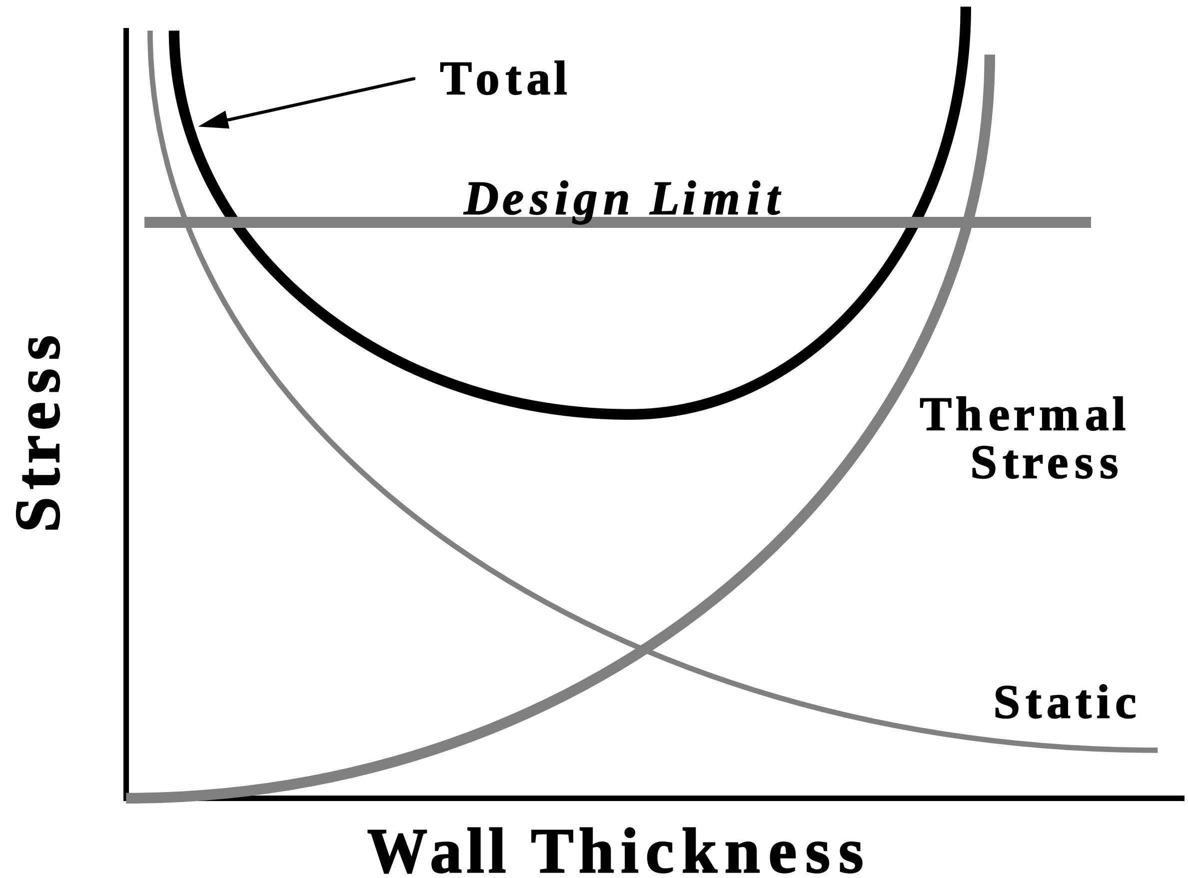


FIG IX-B-12 THERMAL STRESS FIGURE OF MERIT-CTR MATERIAL USING YIELD STRENGTH

First Wall Heat Flux Limits



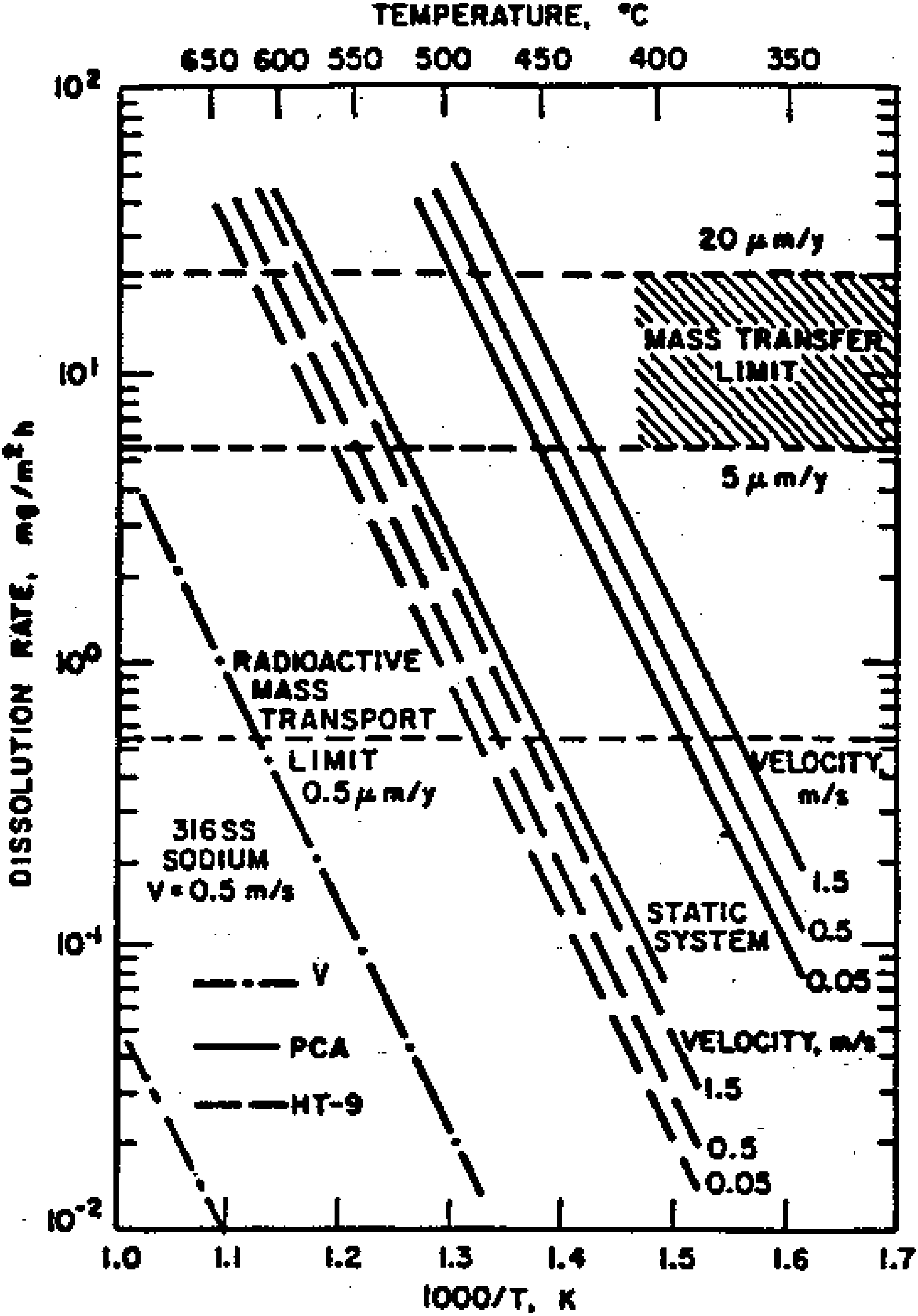


Figure 6.2-4. Effect of temperature on the corrosion rate of PCA and HT-9 alloy in flowing lithium.

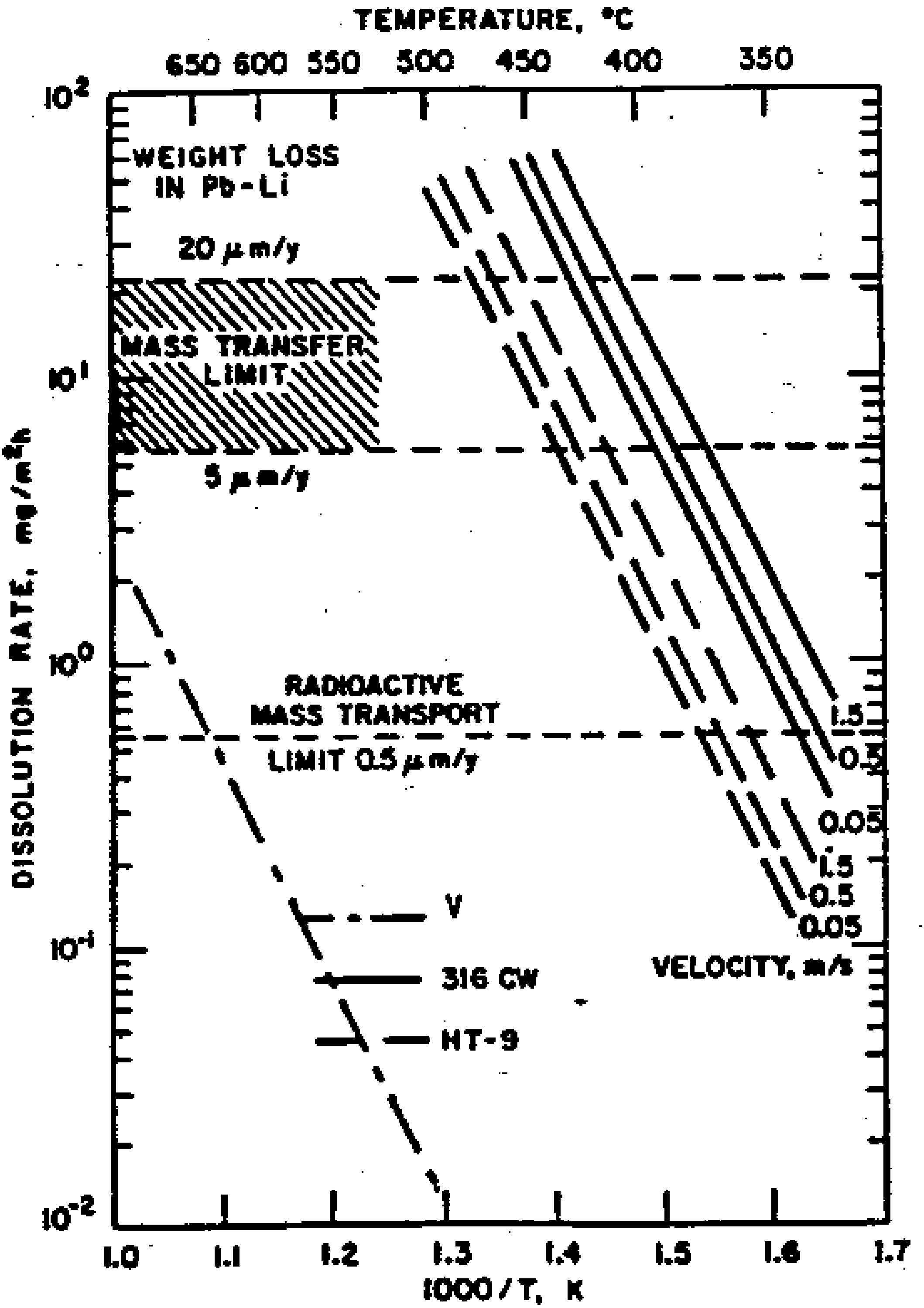


Figure 6.2-5. Effect of temperature on the corrosion rate of 20% cold worked Type 316 stainless steel and HT-9 alloy in flowing Pb-17Li.

TEMPERATURE DEPENDENCE OF THE EQUILIBRIUM DISTRIBUTION COEFFICIENTS FOR OXYGEN BETWEEN SELECTED REFRACTORY METALS AND LITHIUM

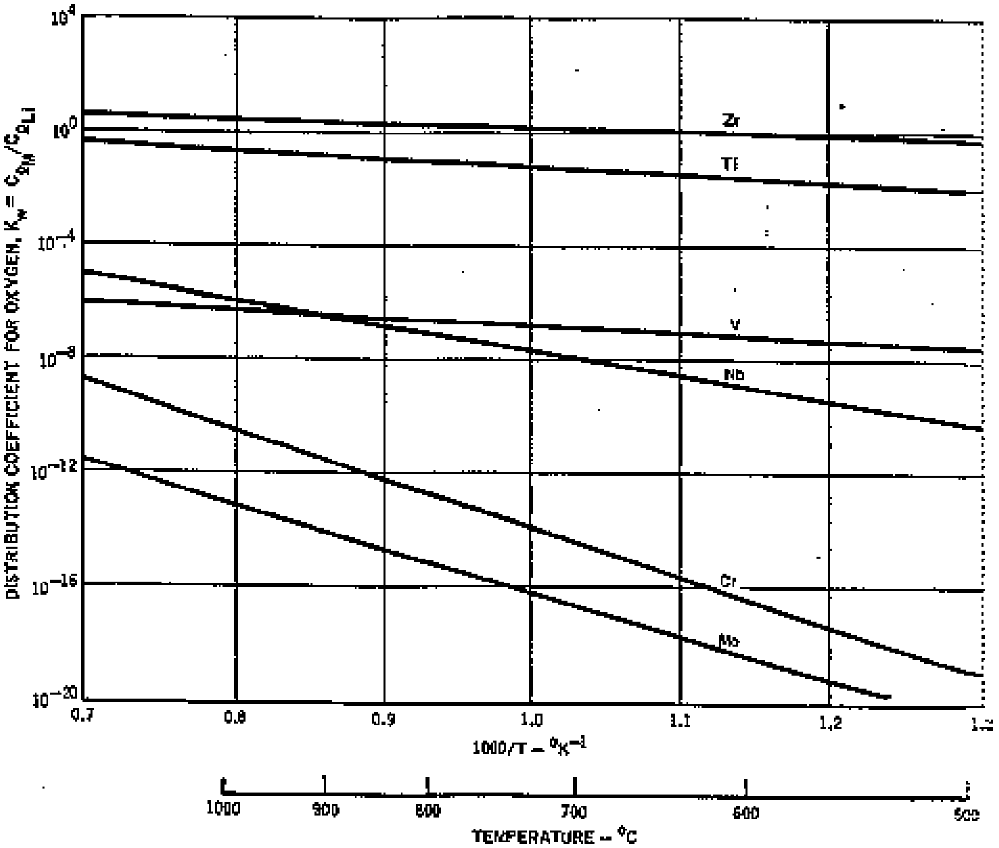
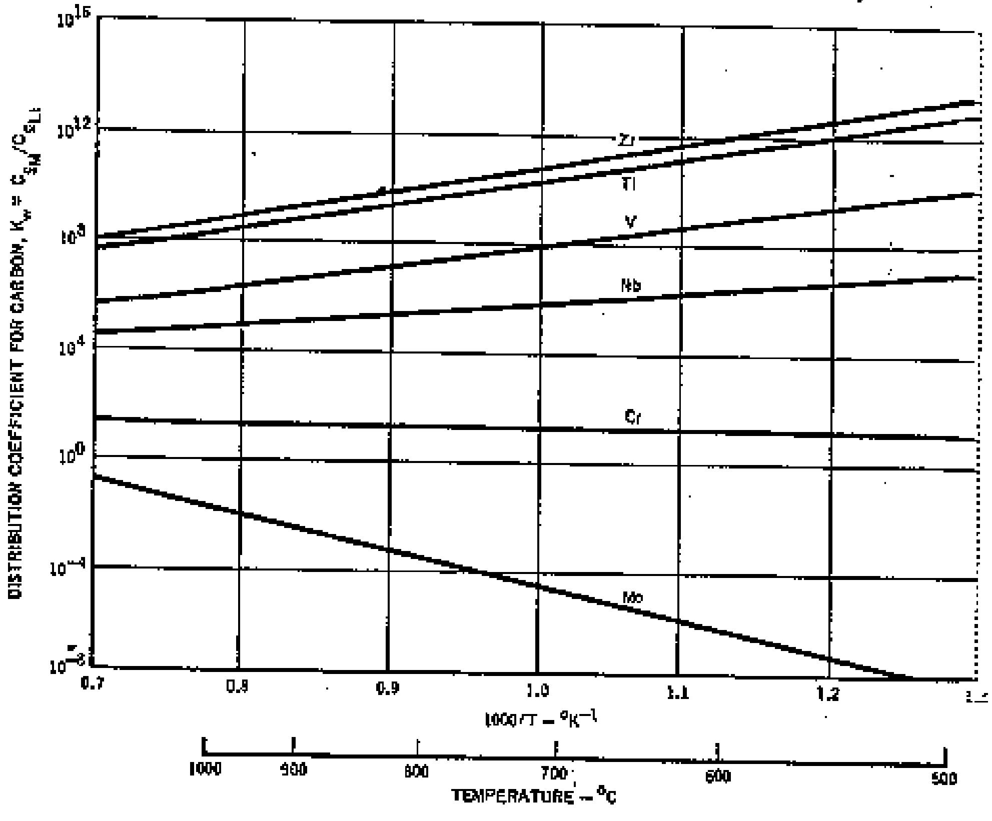


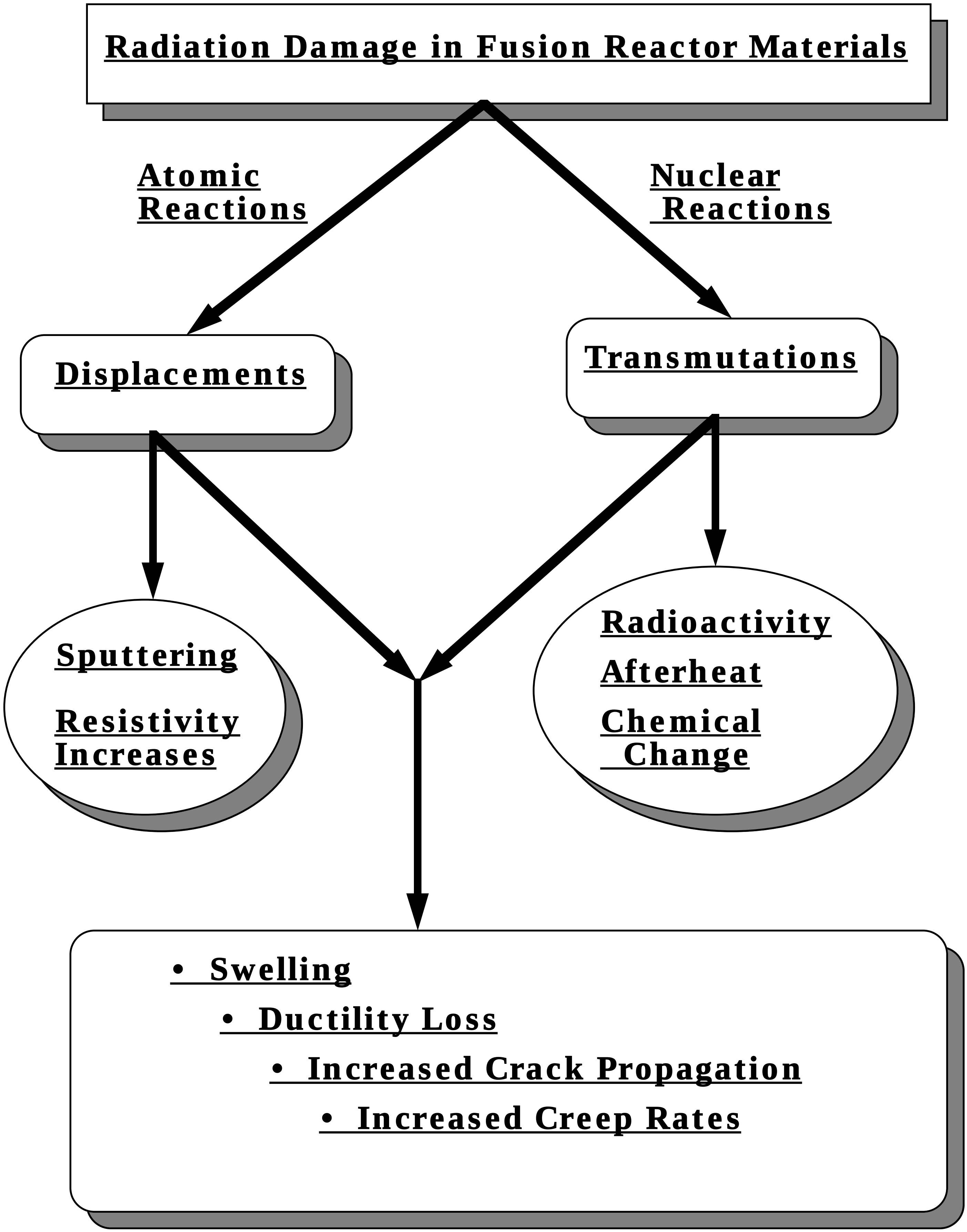
Figure 28

TEMPERATURE DEPENDENCE OF THE EQUILIBRIUM DISTRIBUTION COEFFICIENTS FOR CARBON BETWEEN SELECTED REFRACTORY METALS AND LITHIUM



Compatibility Limits

Alloy	Coolant	Tmax °C
Al	Li	< 200
316 SS	Li	< 550
HT-9	Li	< 550
V	Li	< 800
Nb	Li	< 800
Mo	Li	< 1000
316 SS	Pb-Li	< 450
HT-9	Pb-Li	< 500
V	Pb-Li	????
Nb	Pb-Li	????
Mo	Pb-Li	????
316 SS/HT-9	Helium	< 600
V, Nb	Helium	< 600
Mo	Helium	< 1000


Radiation Damage in Fusion Reactor Materials
Atomic Reactions
Nuclear Reactions
Displacements
Transmutations
Sputtering
Resistivity Increases
Radioactivity
Afterheat
Chemical Change
• Swelling
• Ductility Loss
• Increased Crack Propagation
• Increased Creep Rates

Fundamentals of Radiation Damage

Number of Vacancy/Interstitial Pairs produced by the ith reaction per incident particle of energy E per second , $N_d^i(E)$

$$N_d^i(E) = N_o \int \varphi(E)\sigma^i(E)K(E,T)\nu(T)dT$$

Where:

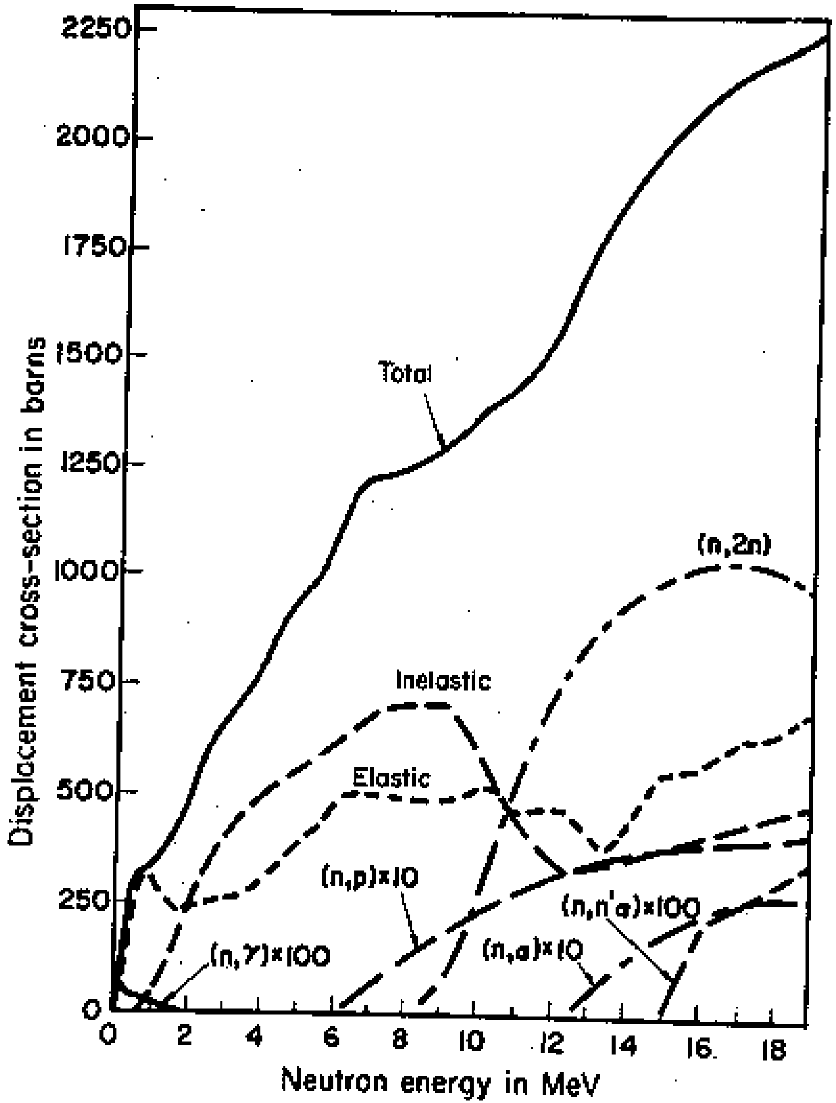
N_o = Atomic Density

ϕ (E) = Flux of particles of energy E

σ^i (E) = Probability that the incident particle with energy E, causing reaction i, will undergo an interaction with a matrix atom

K(E,T) = Probability that if an interaction takes place, it will produce a primary knock-on-atom (PKA) with energy T

ν(T) =Number of atoms subsequently displaced by the PKA



idual contributions to the total niobium displacement cross

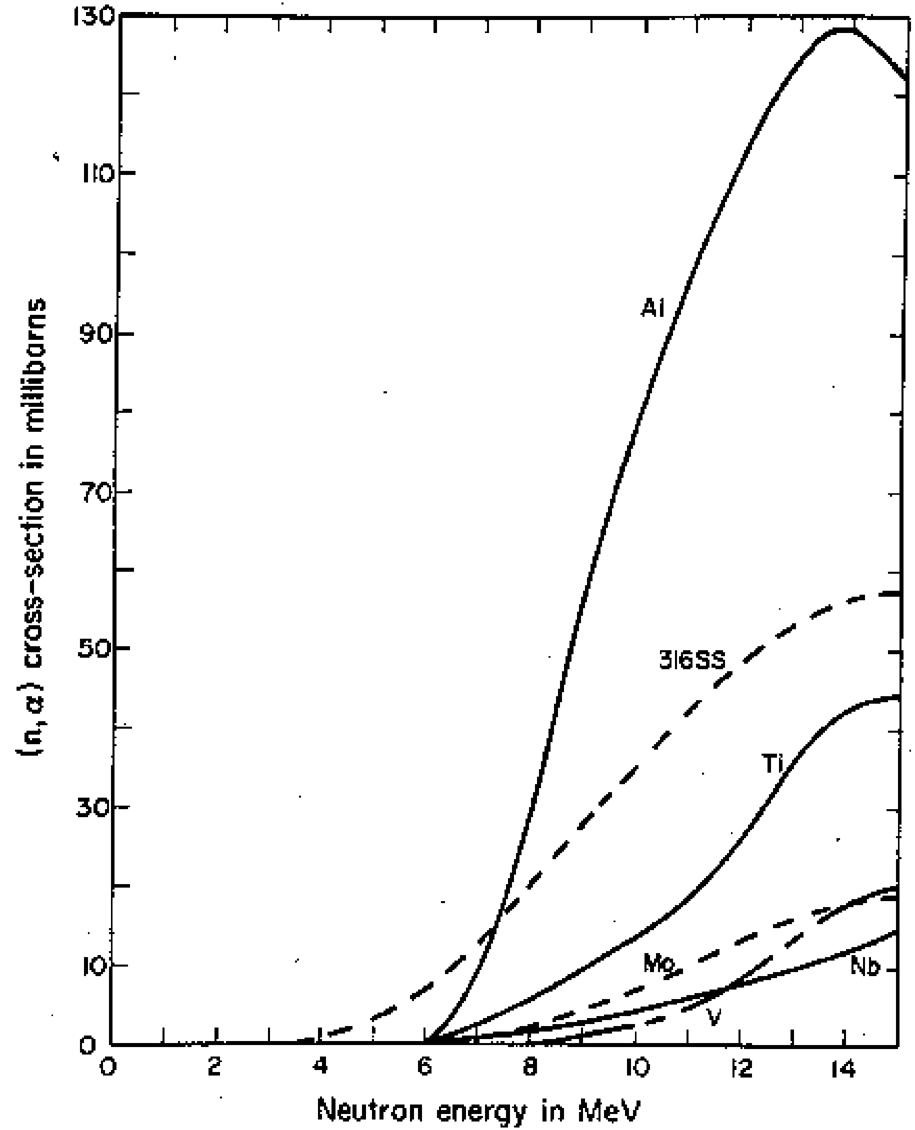
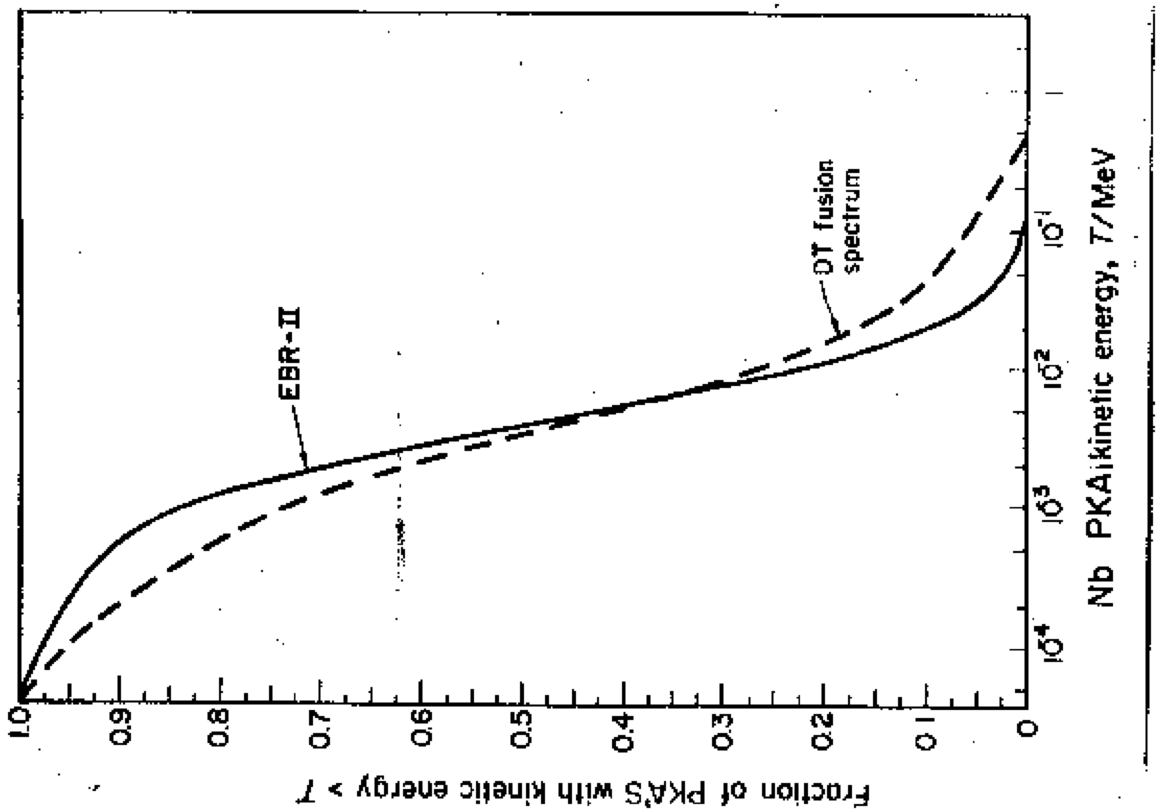
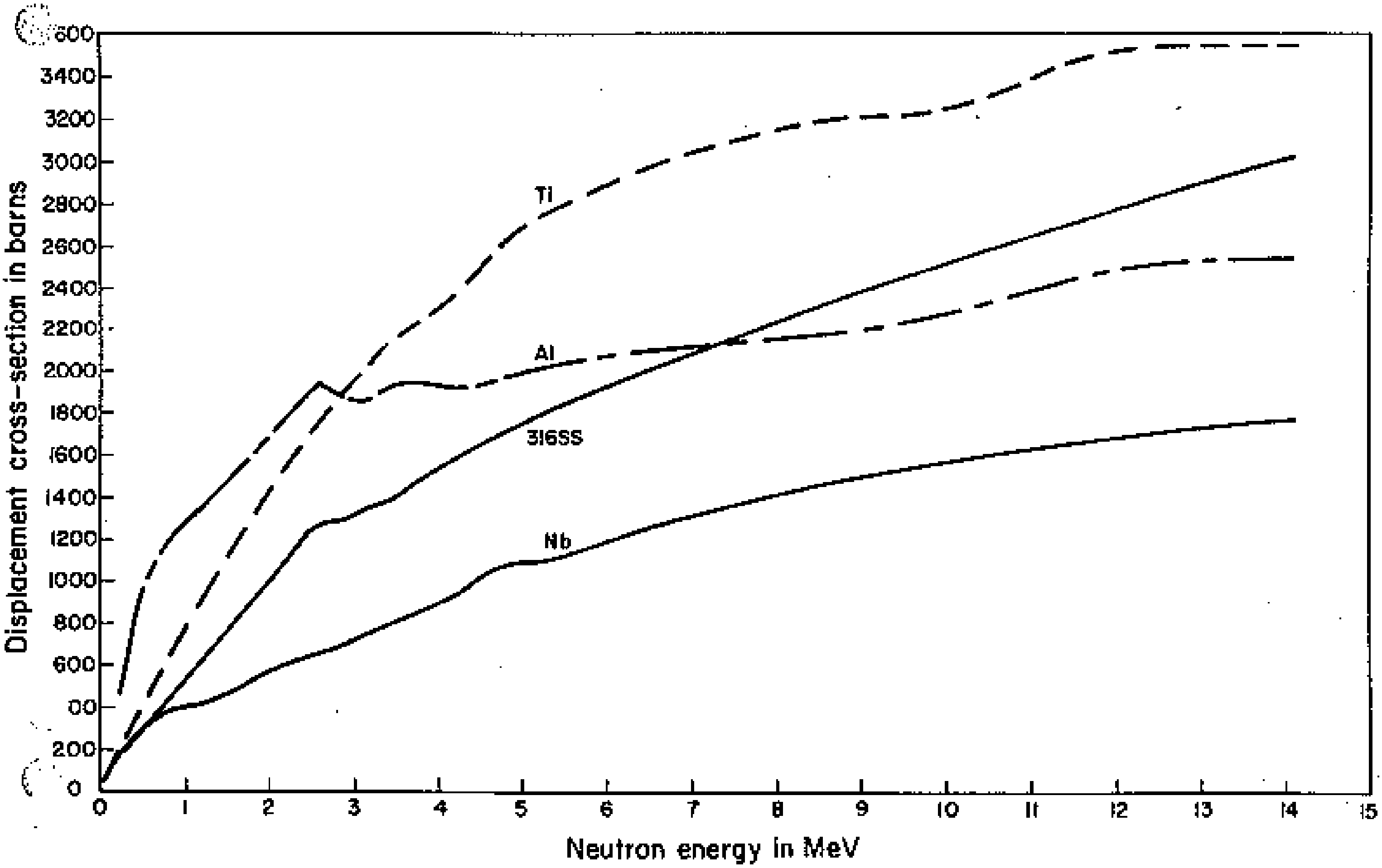


Figure 15. Helium gas production cross-section.


EBR-II
DT fusion spectrum
Nb PKA kinetic energy, T/MeV
Fraction of PKA'S with kinetic energy > T


Ti
Al
316SS
Nb
Displacement cross-section in barns
Neutron energy in MeV

Displacements per $\frac{MW}{m^2}$

Definition of dpa (displacements per atom) is the number of times that an atom is displaced for a given fluence.

$$\frac{N_d}{N_o} = \varphi t \sigma_d$$

Example of 1 $\frac{MW}{m^2}$

$$\varphi = 4.43x10^{13} \frac{n}{cm^2 - s}$$

$$\sigma_d = 3,000b$$

$$\frac{N_d}{N_o t} = 4.43x10^{13} \bullet 3x10^{-21}$$

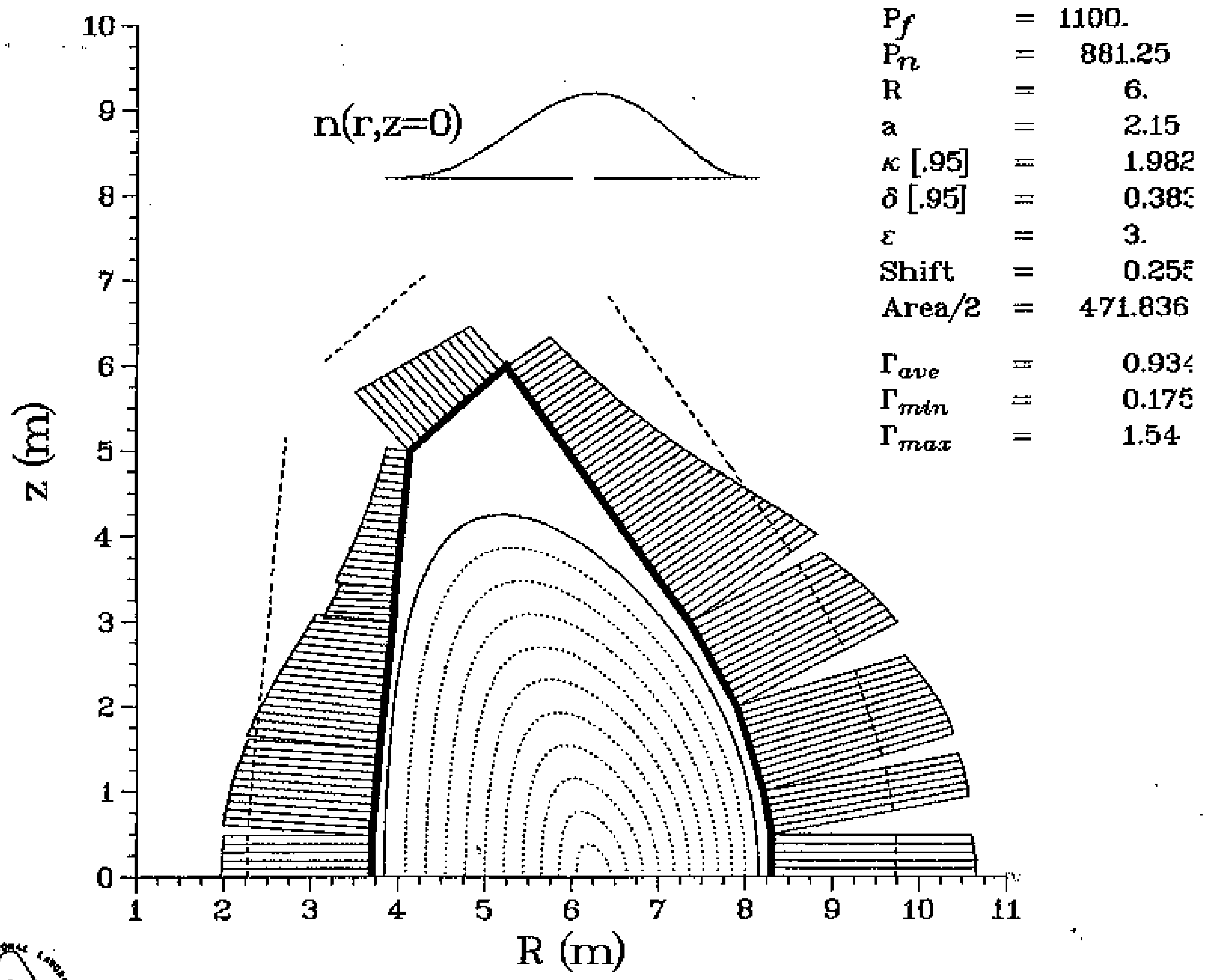
$$= 1.3x10^{-7} \frac{dpa}{s}$$

$$\approx 4 \frac{dpa}{FPY}$$

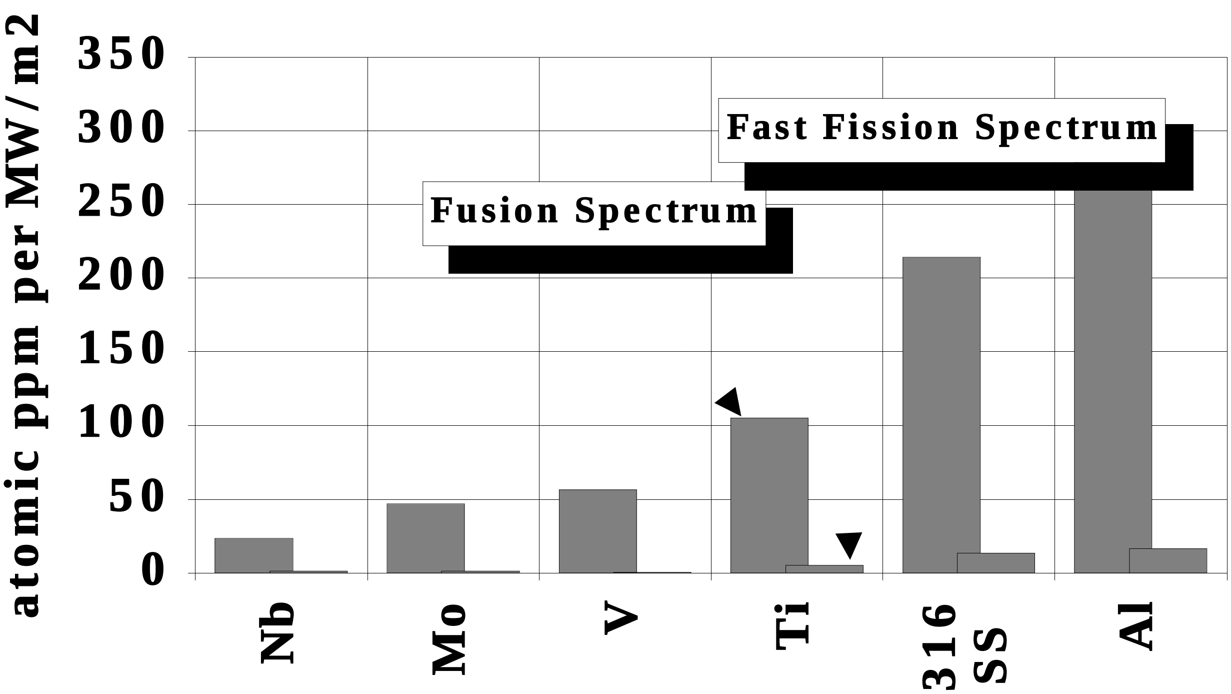
Damage Rate in CTR materials	
Material	**dpa/FPY per MW/m^2**
316 SS	10
V	12
Mo	8
SiC	30
Al	17

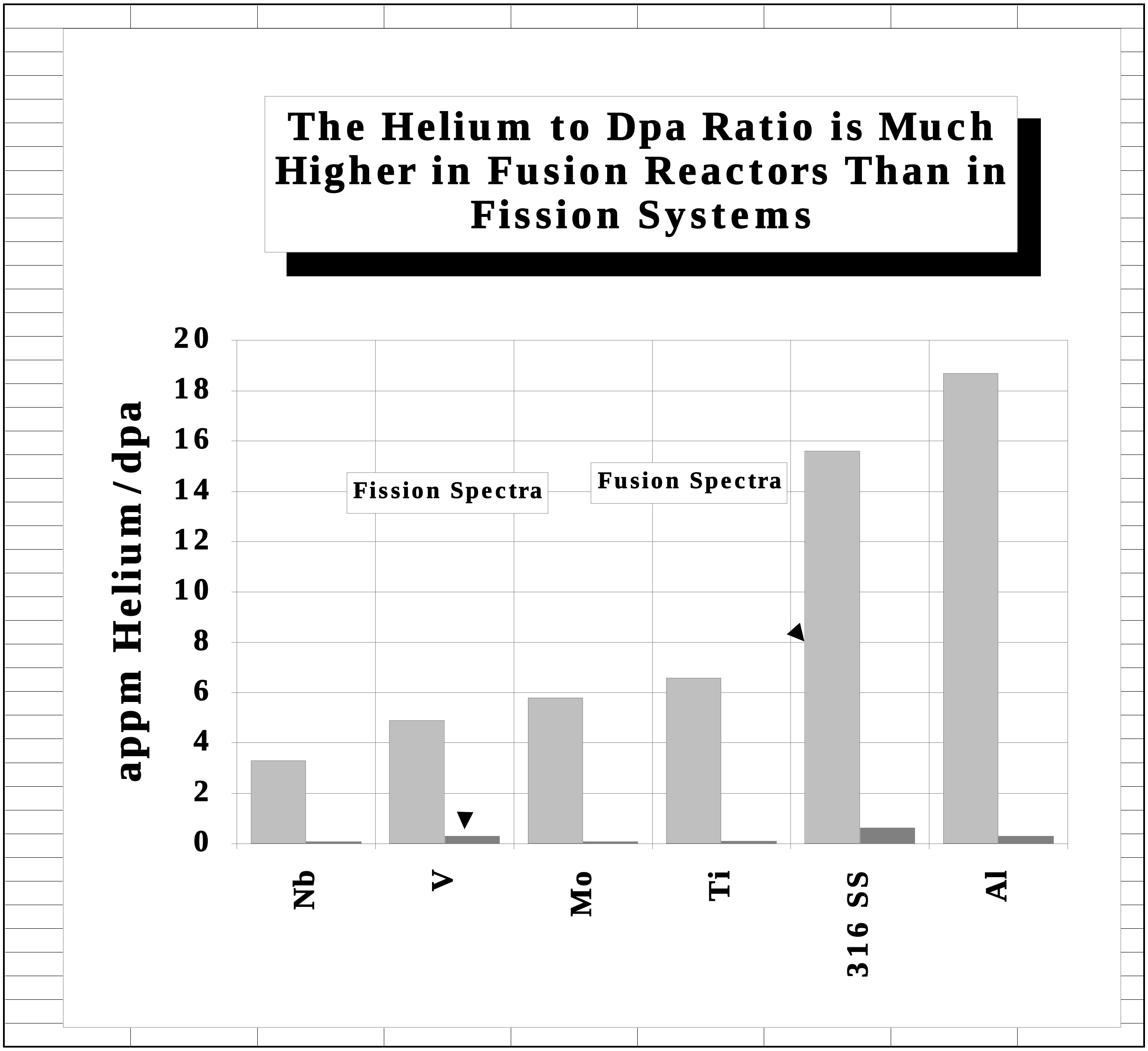
ITER Neutron Wall Loading Distribution

Pysics Phase 1100 MW



The Production of Helium Gas in Metals and Alloys is much Greater than in Fission Reactors




The Helium to Dpa Ratio is Much Higher in Fusion Reactors Than in Fission Systems
appm Helium/dpa
20
18
16
14
12
10
8
6
4
2
0
Fission Spectra
Fusion Spectra
Nb
V
Mo
Ti
316 SS
Al

Swelling

- First discovered in 1986-UK

- Occurs when vacancies collect into clusters which grow and cause the material to expand

- Has been observed in many pure metals and alloys (Mg, Al, V, Fe, Co, Ni, Cu, Nb, Mo, Ta, W, Re, and Pt) and dozens of alloys.

- Generally occurs between 30 and 50% of the absolute melting point.

(Figures)

- Usually try to keep swelling <<10% (i.e., 1-2%)

- Limits the operating life to 2-3 FPY's in austenitic steels and 5-7 FPY's in ferritic steels.

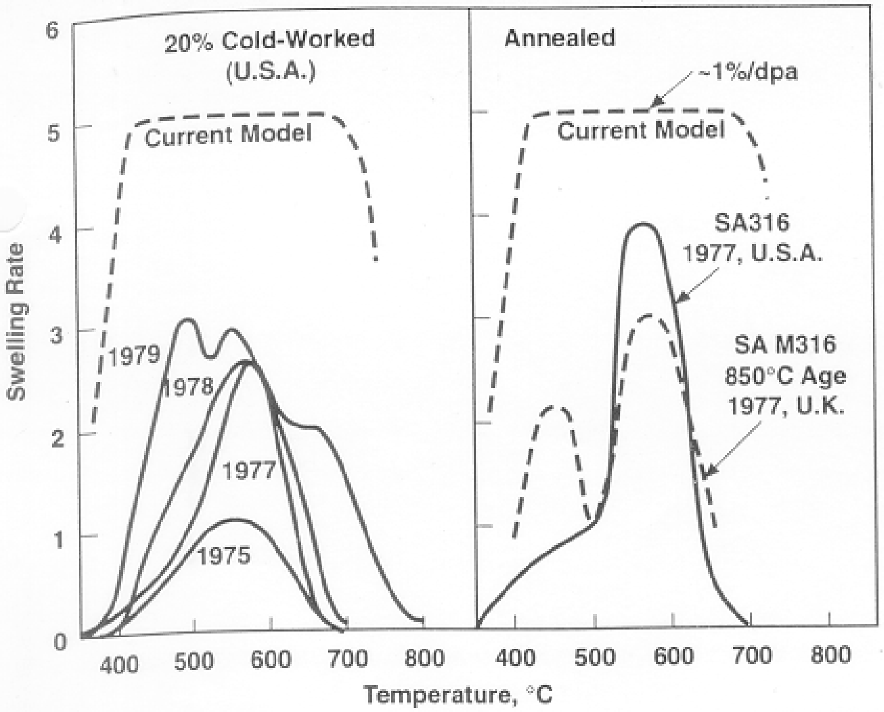


Figure 6-22. Chronological evolution of swelling predictions for AISI 316 in the U.S. LMR materials program, reflecting the tendency of predictions to increase as data became available at progressively higher swelling levels (Garner, previously unpublished). The swelling rate is in units of $\%/10^{22}$ n cm^{-2} ($E > 0.1$ MeV).

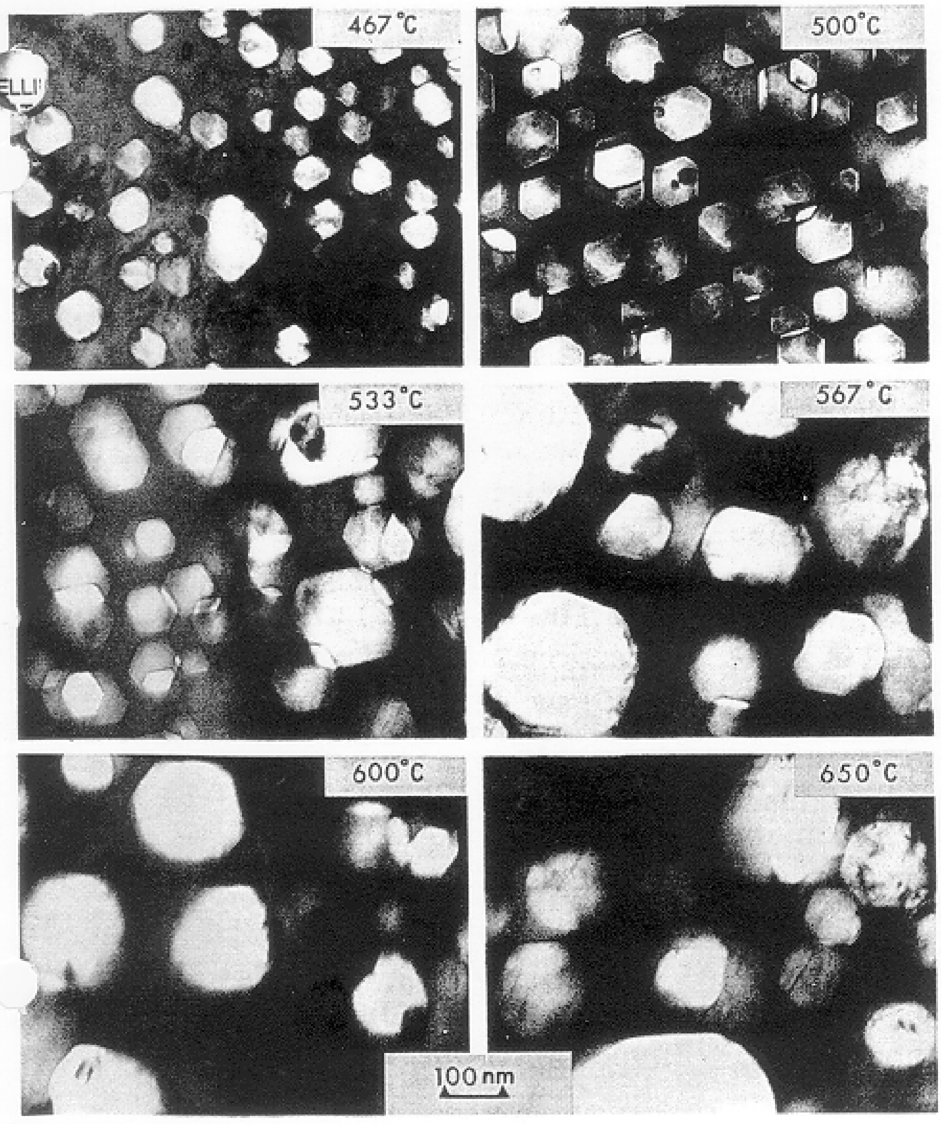


Figure 6-23. Temperature dependence of void swelling observed in FFTF first core heat CN-13 of 20% cold worked AISI 316 at $\approx 1.4 \times 10^{23}$ n cm^{-2} ($E > 0.1$ MeV) or ≈ 70 dpa (courtesy of W. J. S. Yang of Westinghouse Hanford Company).

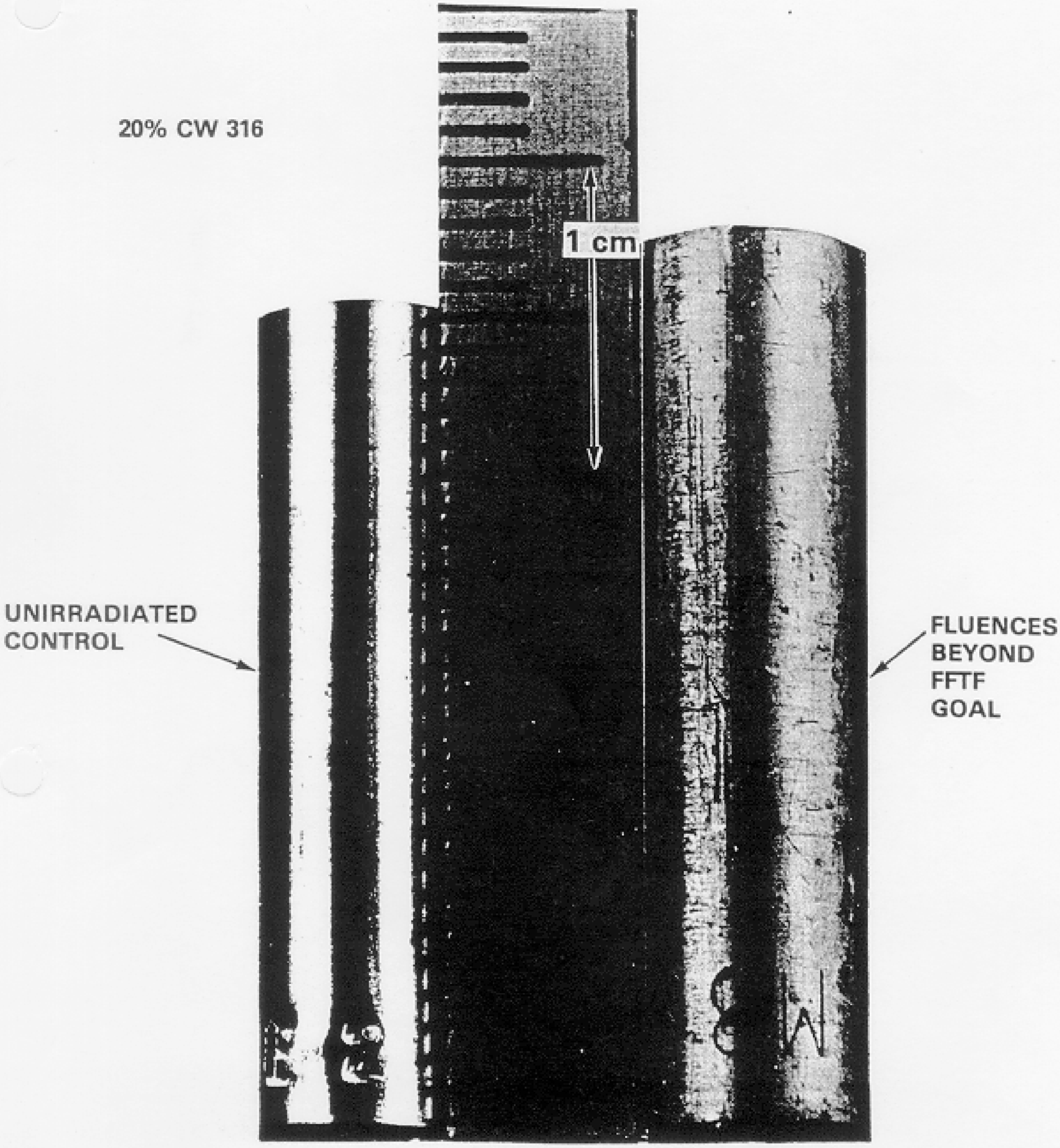


Figure 6-24. Easily observed swelling ($\approx$10% linear, $\approx$33% volumetric) in unfueled 20% cold worked AISI 316 cladding tube at 1.5×10^{23} n cm^{-2} ($E > 0.1$ MeV) or $\approx$75 dpa at 510 °C in EBR-II (after Straalsund et al., 1982). Note that, in the absence of physical restraints, all relative proportions are preserved during swelling.

SWELLING ESTIMATES OF TYPE 316
STAINLESS STEEL 20% COLD WORKED
(AUG. 1969)

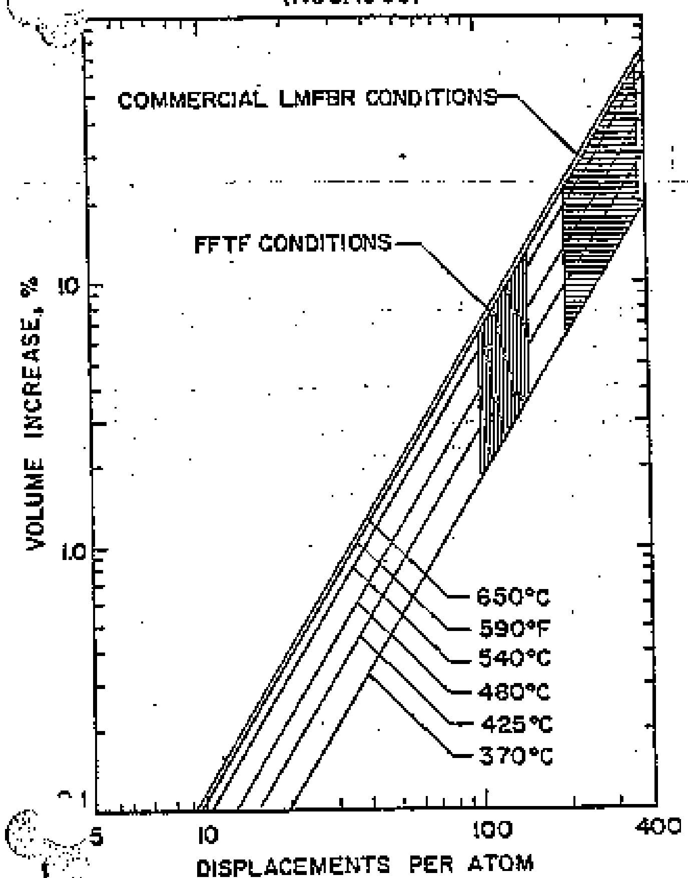
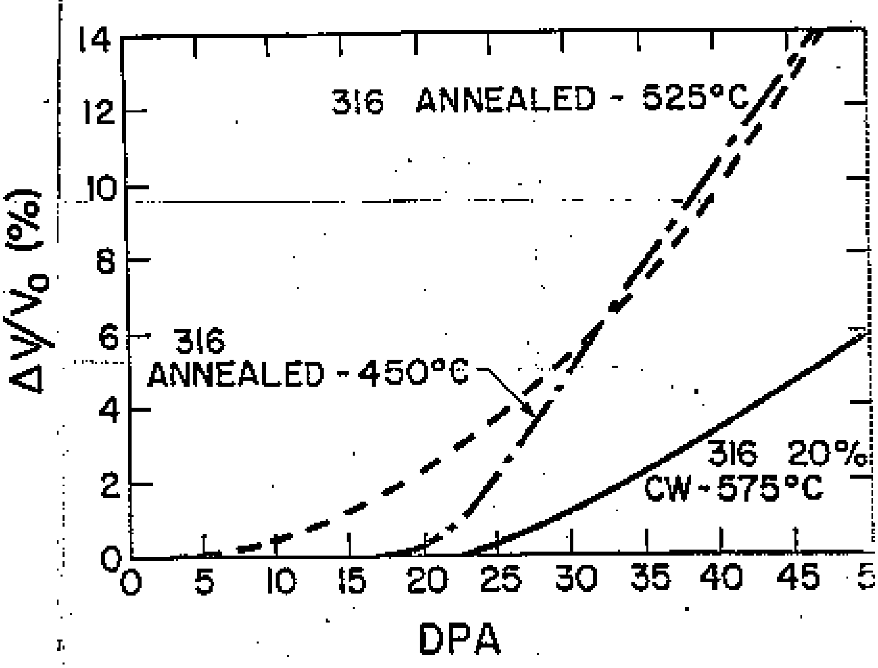


FIGURE 5



TYPICAL SWELLING IN AUSTENITIC STEELS

PREDICTED SWELLING FOR
SOLUTION TREATED 316 STAINLESS STEEL
AT 2.5×10^{23} n/cm^2 (E>0.1 MeV)

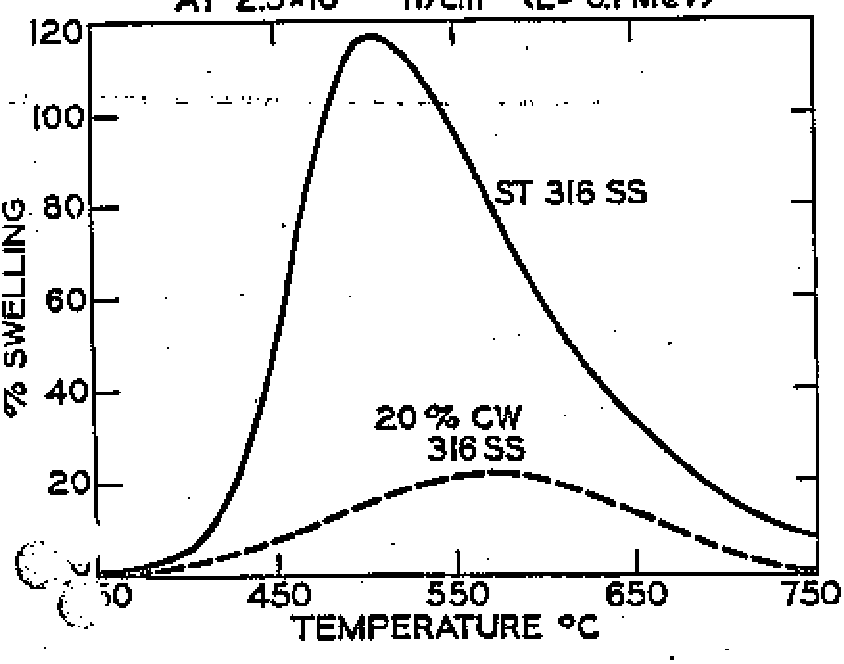
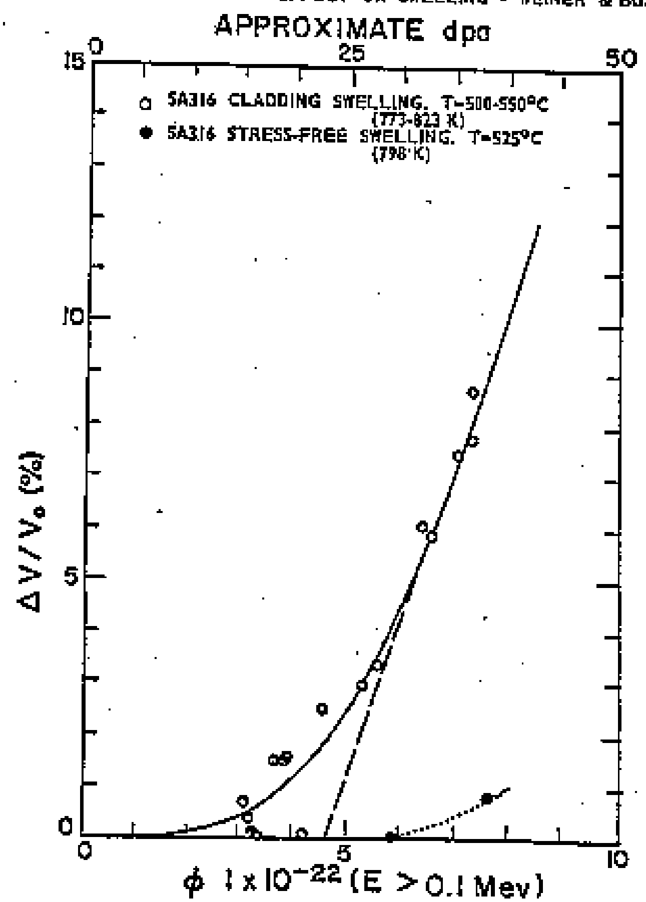


FIGURE 21 STRESS EFFECT ON SWELLING - WEINER & BOLTAX



Embrittlement

- Loss of ductility due to helium collecting at grain boundaries.

- Try to keep the uniform elongation > 1%

- In ferritic steels, the shift in the ductile to brittle transition temperature is the important thing.

(Figures)

Overall Conclusions

- In DT devices , displacement and transmutation effects will limit useful lifetimes to a few full power years. Hence replacement of the FW, blanket, components will have to be done on a regularly scheduled basis.

- Use of advanced fuels will drop the neutron wall loading by a factor of ≈ 30 which means that the structural materials can last for the life of the reactor.

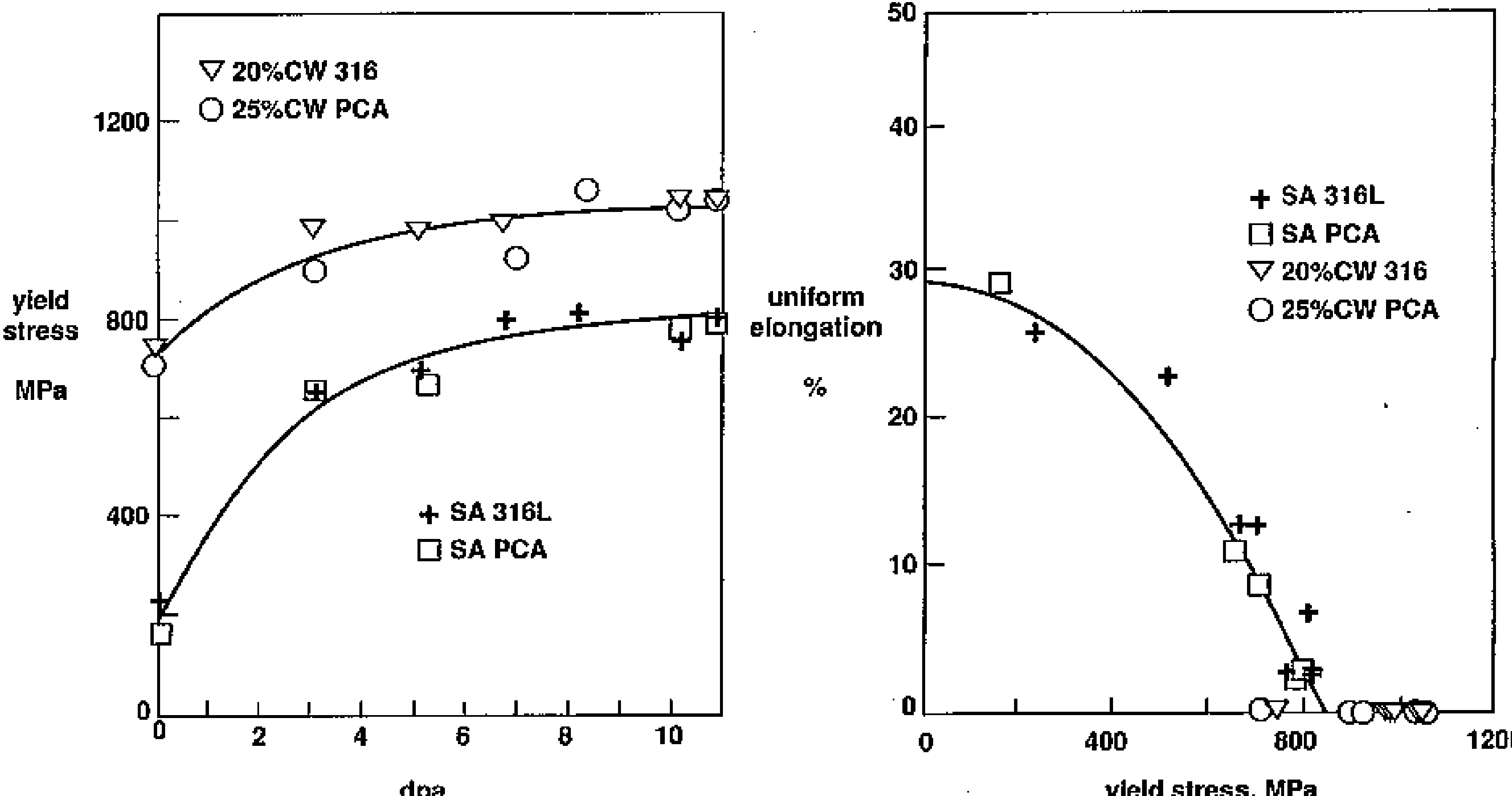


Figure 6-146. Hardening and ductility loss observed in two stainless steels irradiated in the HFIR, HFR, and R2 mixed spectrum reactors at 250°C at helium/dpa ratios ranging from 10 to 35 appm/dpa (after Elen and Fenici, 1992).

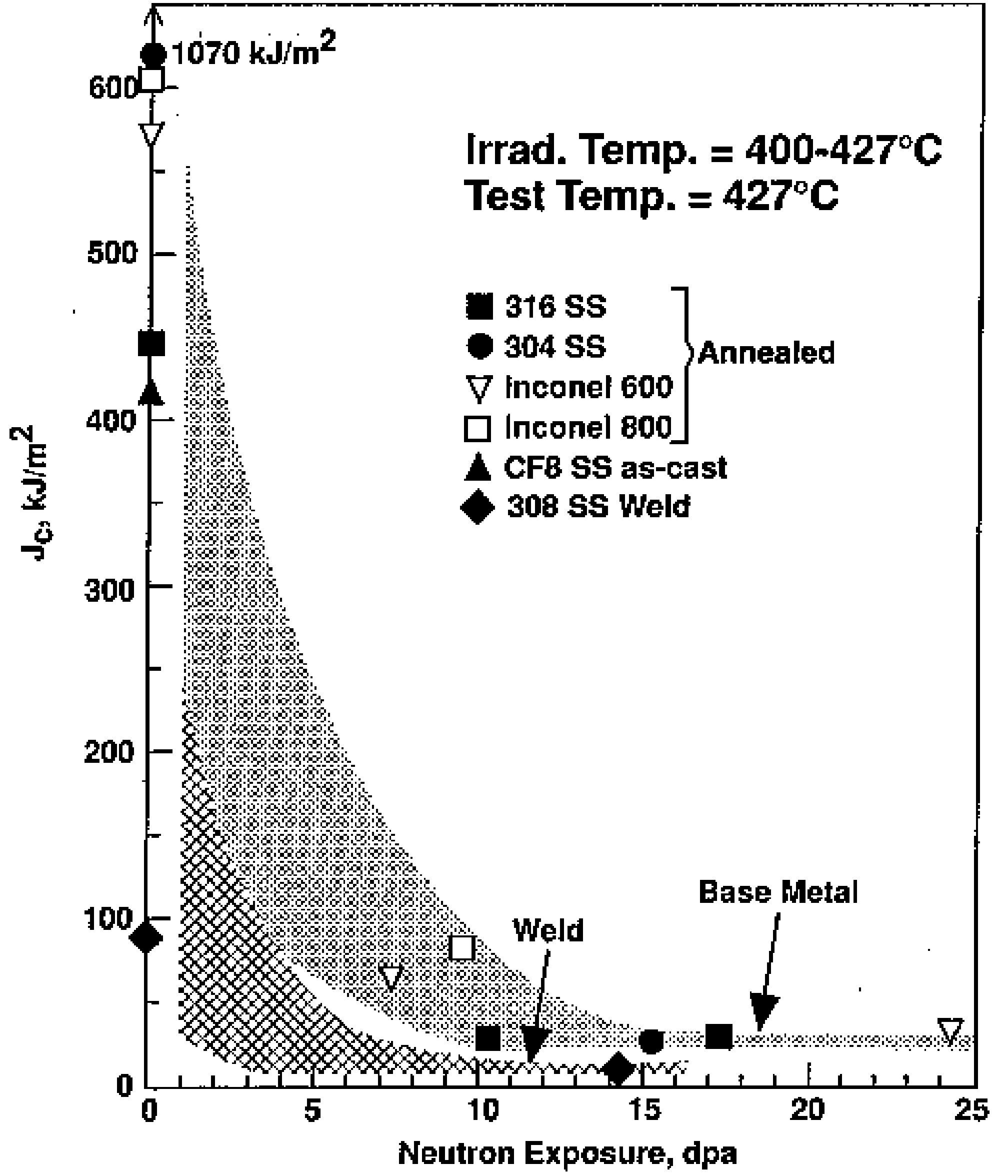


Figure 6-163. Irradiation-induced evolution of J_c fracture toughness in various austenitic steels and welds (after Mills, 1982).

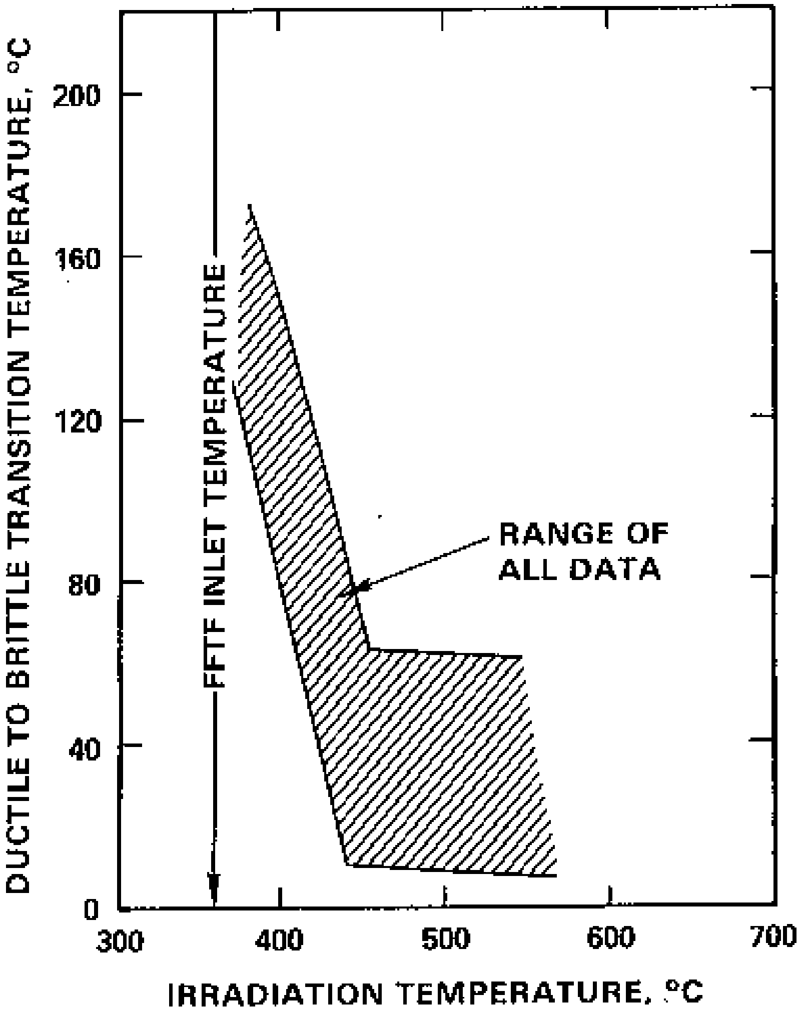


Figure 6-168. Dependence of DBTT on irradiation temperature for HT9 irradiated in FFTF (unpublished data courtesy of W. L. Hu, Westinghouse Hanford Company).

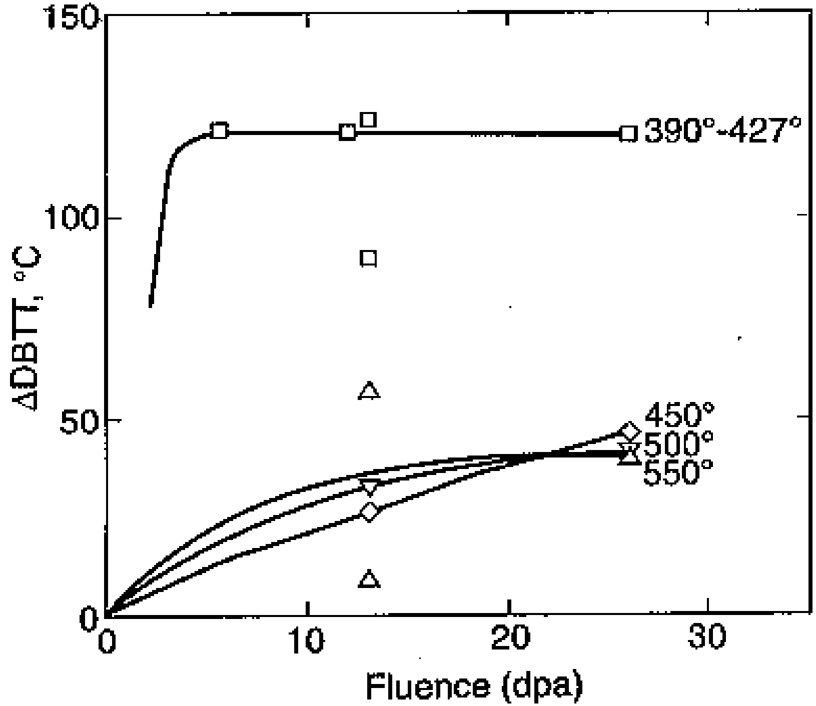


Figure 6-170. Shift in ductile to brittle transition temperature in HT9 as a function of neutron fluence and irradiation temperature (after Powell et al., 1986).

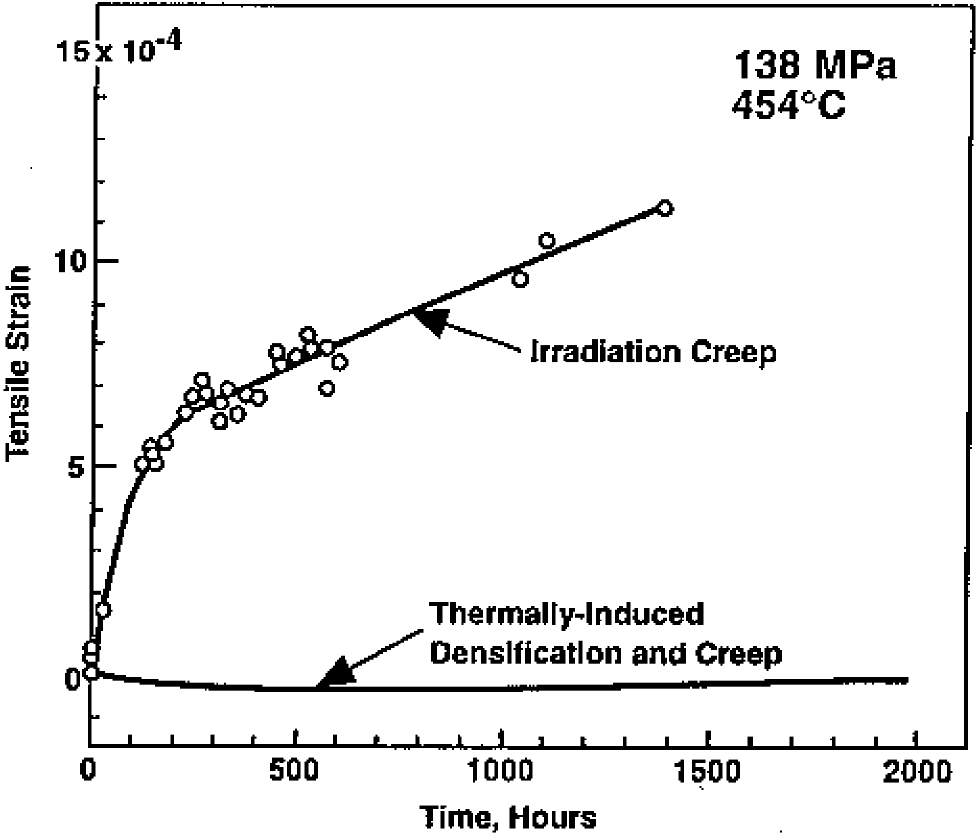


Figure 6-92. Comparison of creep rates observed in 20% cold worked 316 stainless steel in uniaxial tests during thermal aging or neutron irradiation in EBR-II (after Gilbert et al., 1972).

Criteria for Selecting First Wall Materials in Fusion Reactors*

Criteria	Favored Materials	Less Favored
Radiation Damage and Lifetime		
1) Swelling	Ti, FS**, V, Mo, AS**	Al, C, SiC
2) Embrittlement	AS, Ti	FS, V, Mo, C, SiC
Chemical Compatibility		
1) Lithium	Mo, V, FS, AS, Ti	(SiC, Al, C)
2) Helium (impurities)	Mo, FS, AS, C, SiC	Ti, Al, (V)
3) Pb-Li Alloys	Mo, V, FS, AS, Ti, SiC, C	Al
4) Water	AS, FS, Mo, Ti, Al	V, (SiC, C)
Mechanical and Thermal		
1) Yield Strength	Mo, Ti, V, FS, AS	SiC, C, Al
2) Embrittlement	AS, Ti, Al, Mo, FS	V, SiC, C
3) Creep Strength	Mo, V, FS, AS, Ti	C, SiC, Al
4) Thermal Stress $\equiv \frac{2\sigma_y k(1-\upsilon)}{\alpha E}$	Mo, Al, V	Ti, FS, AS
Fabricability and Joining	AS, Al, FS, Ti	V, Mo, C, SiC
Database and Industrial Capability	AS, FS, Al, Ti, C	SiC, Mo, V
Long-lived Radioactivity	V, C, SiC, Ti, Al	FS, AS, Mo
Cost	Al, AS, FS, C	Ti, V, SiC, Mo
Resource Availability (USA)	C, SiC, Al, Ti, Mo, AS, FS	V

* Note: Only Base Metal Listed (i.e., Ti for Ti alloys, V for V alloys, etc.)
** AS for austenitic stainless steel, FS for ferritic steel
( ) Materials in parentheses are generally unacceptable with coolant.