Structural Materials Database and Operating Temperature Limits

S.J. Zinkle[1] and A. El-Azab[2]

[1]Oak Ridge National Lab
[2]UCLA

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Factors Affecting Selection of Structural Materials

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

Possible Structural Materials for High Wall Loading Concepts

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

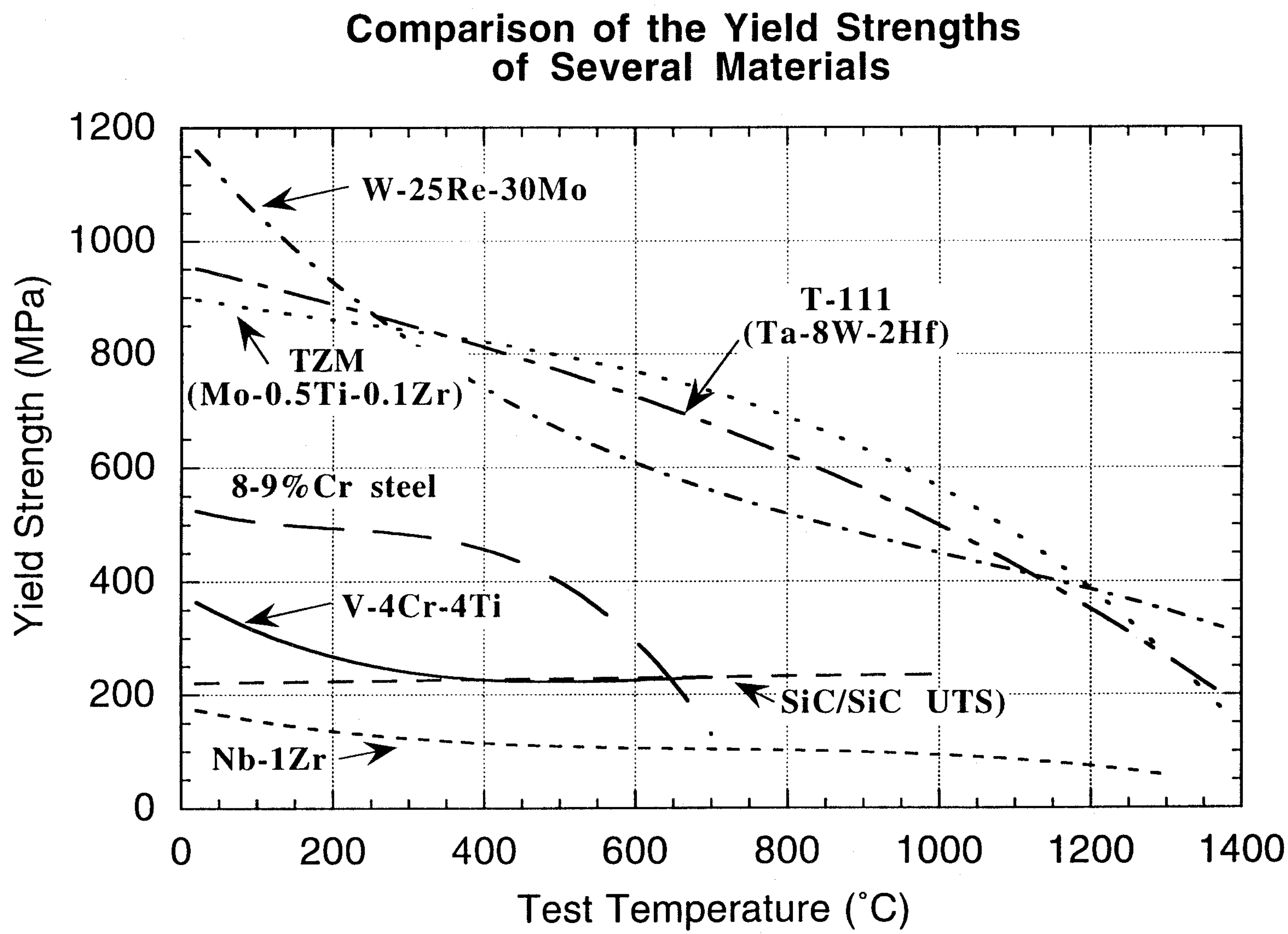
- **Refractory alloys**
  - Nb-1Zr
  - Nb-18W-8Hf
  - T-111 (Ta-8W-2Hf)
  - TZM (Mo-0.5Ti-0.1Zr-0.02C)
  - Mo-Re
  - W-25Re

- **Ni-based superalloys**

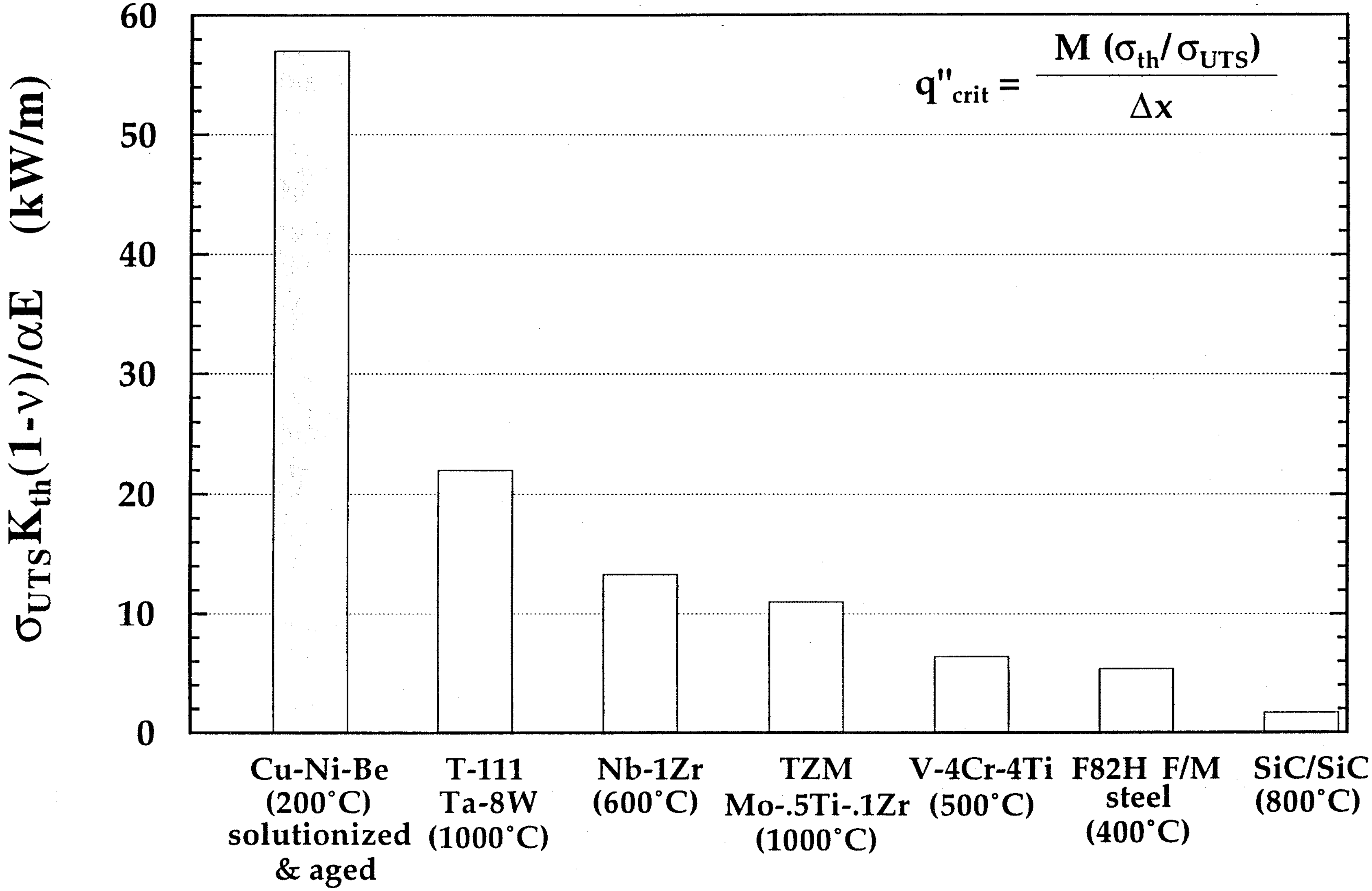
- **Porous-matrix metals and ceramics**

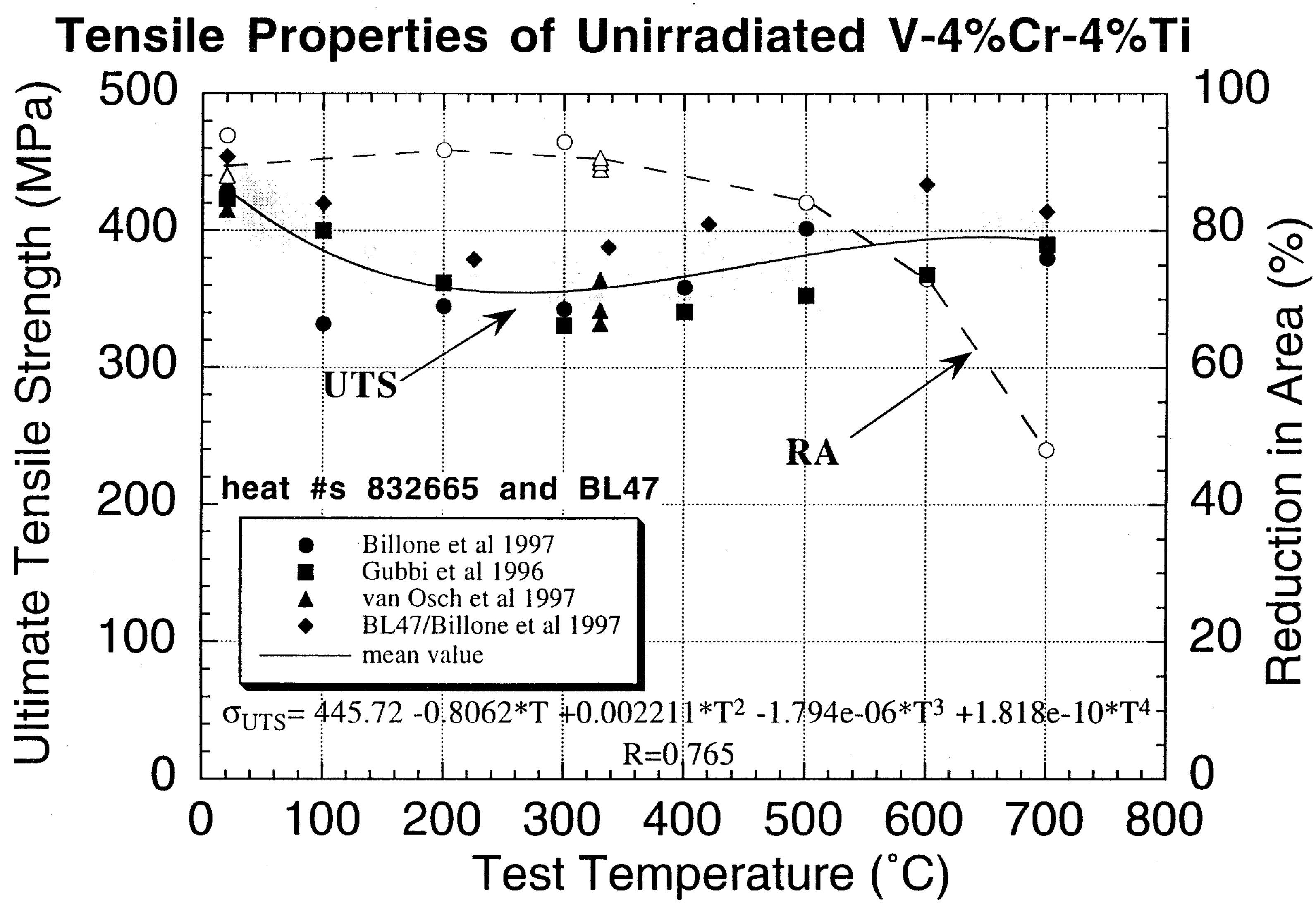
- **Intermetallics**
  - TiAl
  - Fe_3Al

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

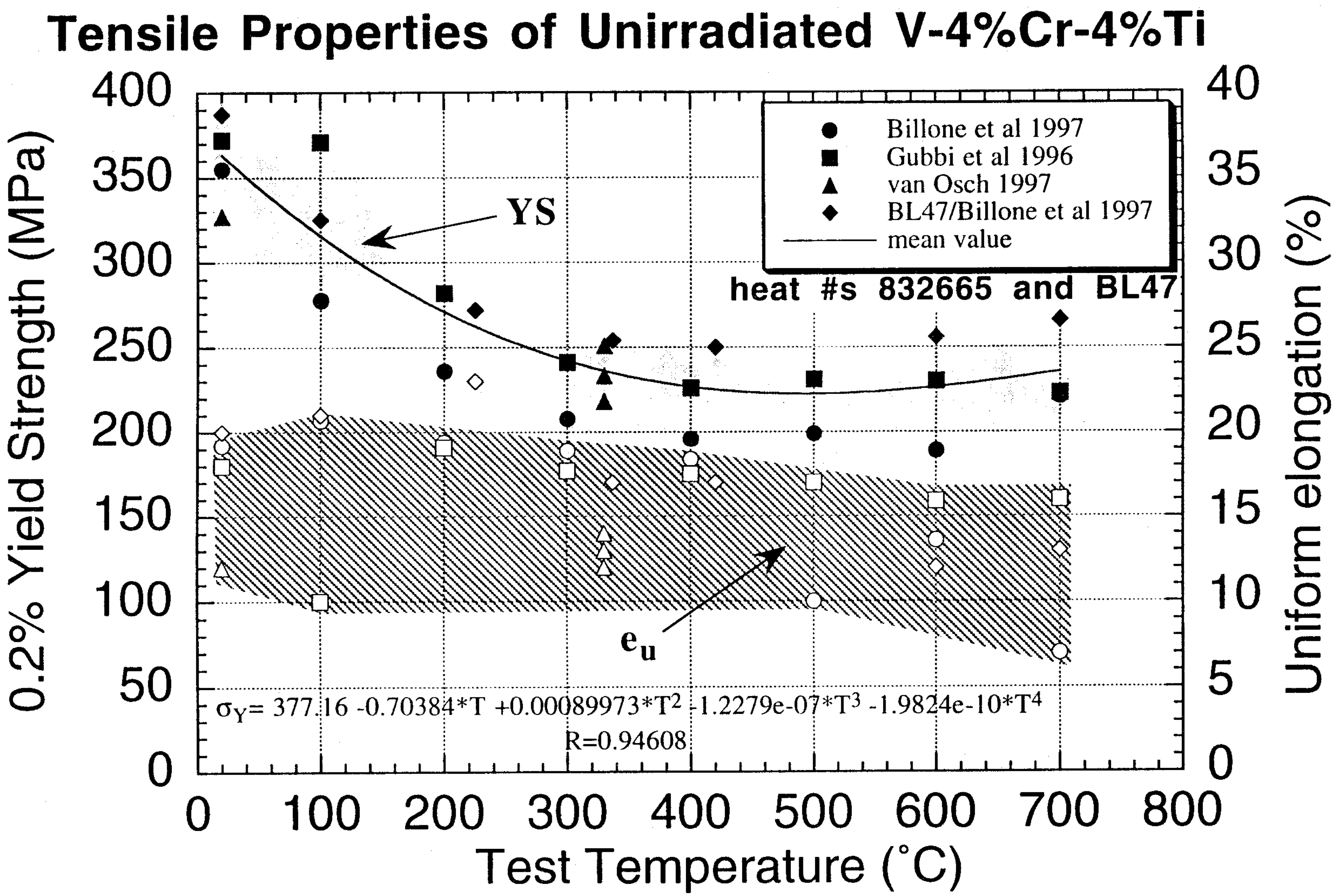

Comparison of the Yield Strengths
of Several Materials
W-25Re-30Mo
T-111
(Ta-8W-2Hf)
TZM
(Mo-0.5Ti-0.1Zr)
8-9%Cr steel
V-4Cr-4Ti
SiC/SiC UTS)
Nb-1Zr
Yield Strength (MPa)
Test Temperature (˚C)
0
200
400
600
800
1000
1200
1400

COMPARISON OF THERMAL STRESS PARAMETERS



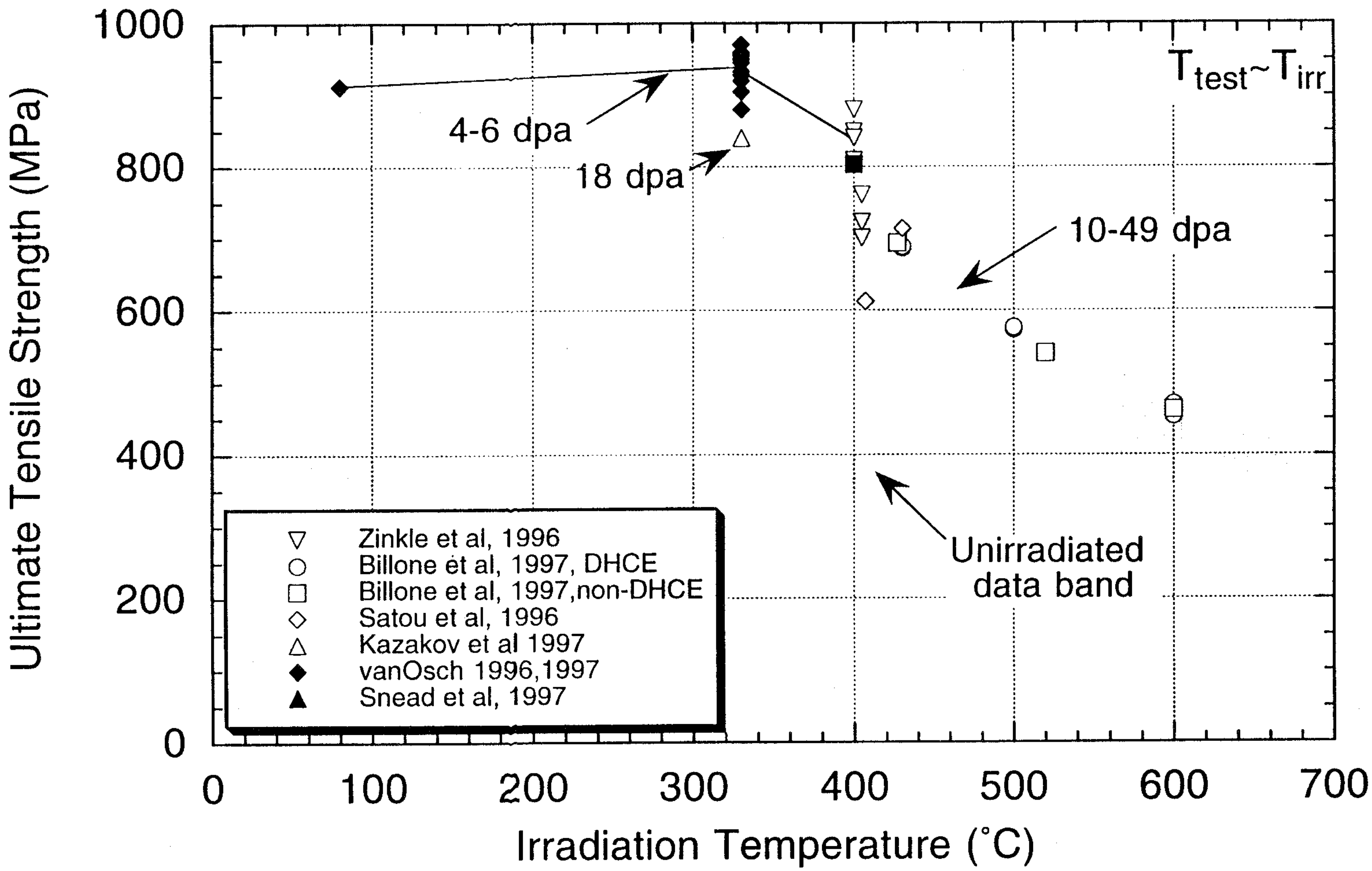


Tensile Properties of Unirradiated V-4%Cr-4%Ti
Ultimate Tensile Strength (MPa)
Reduction in Area (%)
Test Temperature (˚C)
0
100
200
300
400
500
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800
UTS
RA
heat #s 832665 and BL47
Billone et al 1997
Gubbi et al 1996
van Osch et al 1997
BL47/Billone et al 1997
mean value
σ_{UTS}= 445.72 -0.8062*T +0.002211*T^2 -1.794e-06*T^3 +1.818e-10*T^4
R=0.765

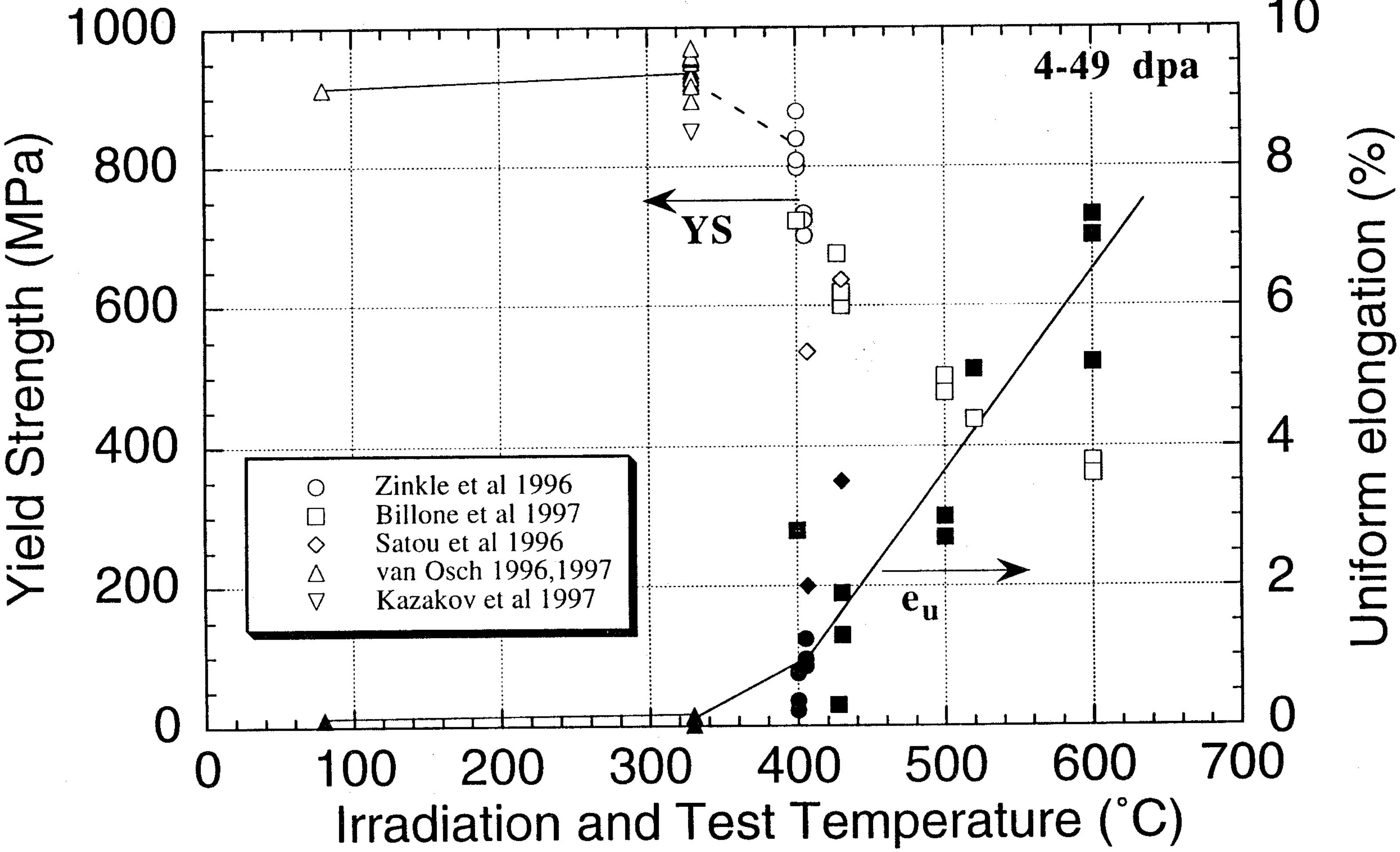


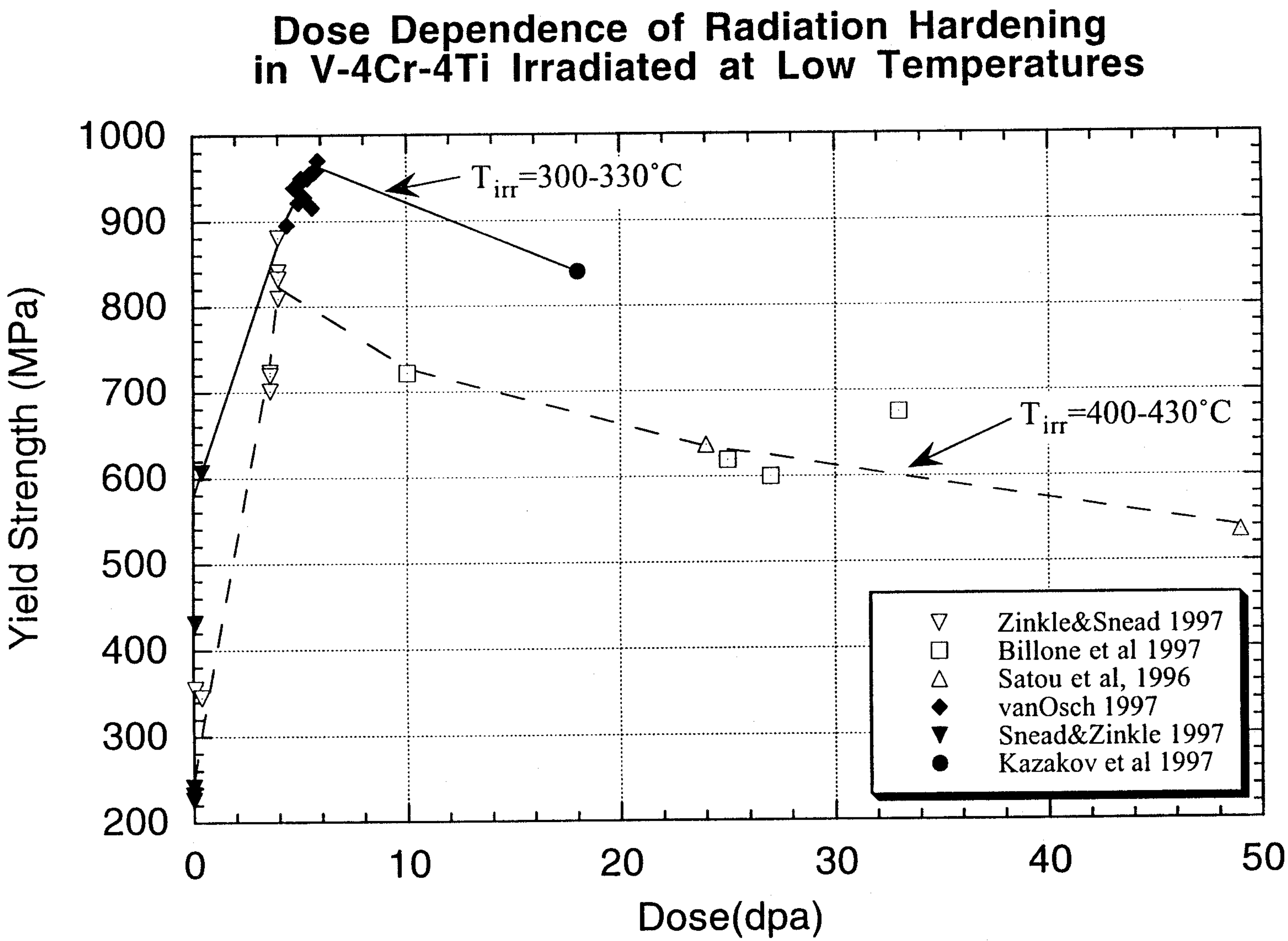
Tensile Properties of Unirradiated V-4%Cr-4%Ti
Billone et al 1997
Gubbi et al 1996
van Osch 1997
BL47/Billone et al 1997
mean value
heat #s 832665 and BL47
YS
e_u
σ_Y= 377.16 -0.70384*T +0.00089973*T^2 -1.2279e-07*T^3 -1.9824e-10*T^4
R=0.94608
0.2% Yield Strength (MPa)
Uniform elongation (%)
Test Temperature (˚C)

Effect of Dose and Irradiation Temperature on the Tensile Strength of V-(4-5%)Cr-(4-5%)Ti Alloys



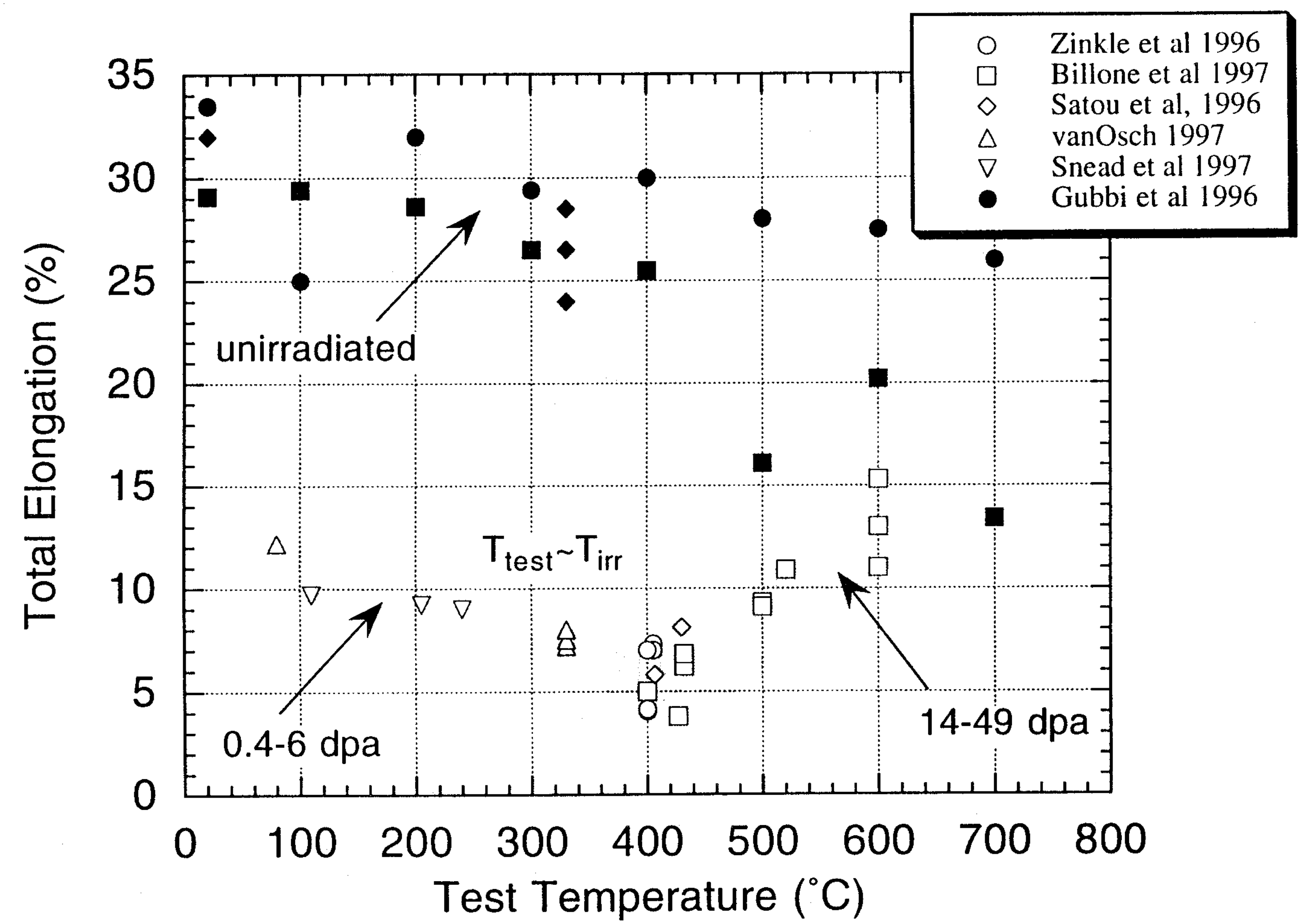
Tensile Properties of Irradiated V-(4-5)%Cr-(4-5)%Ti Alloys



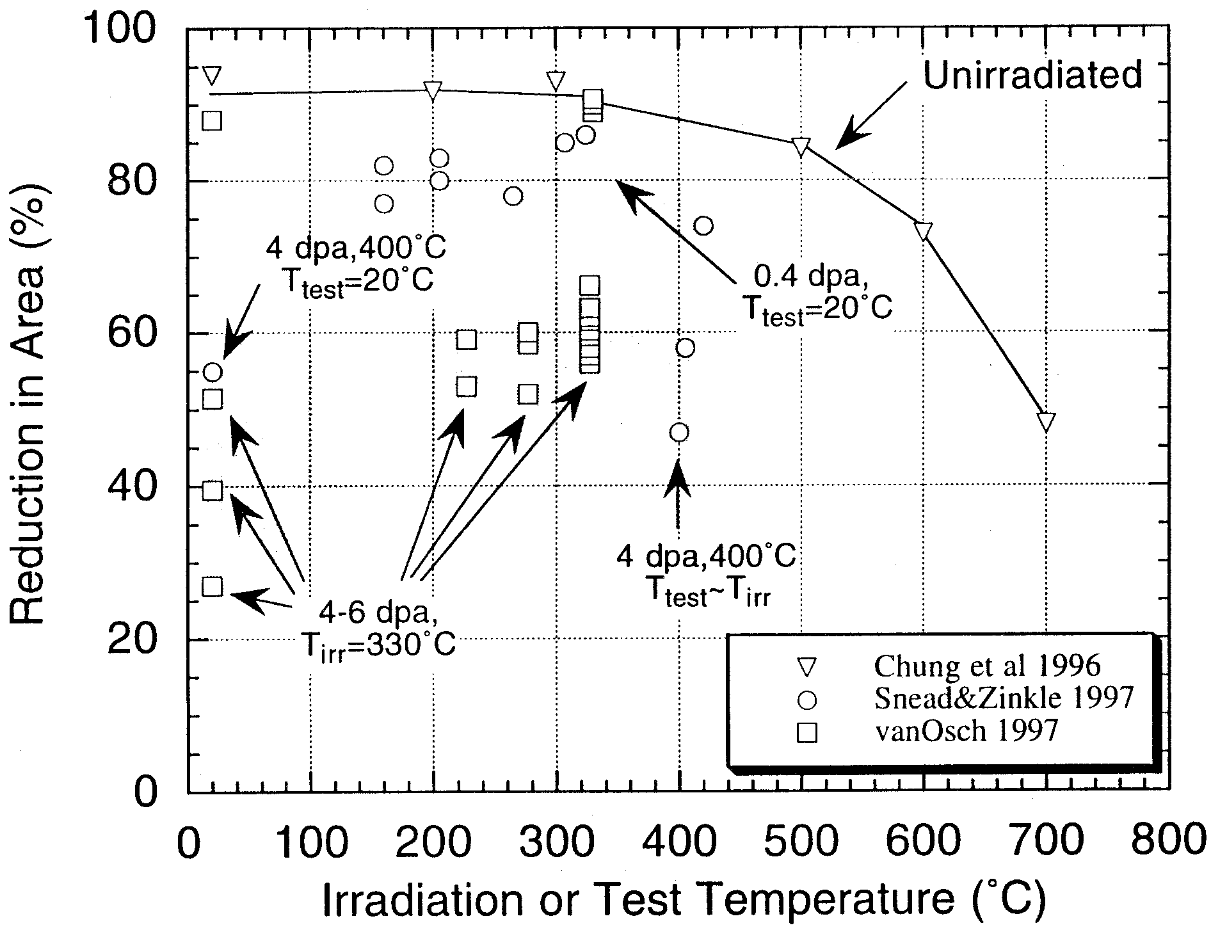


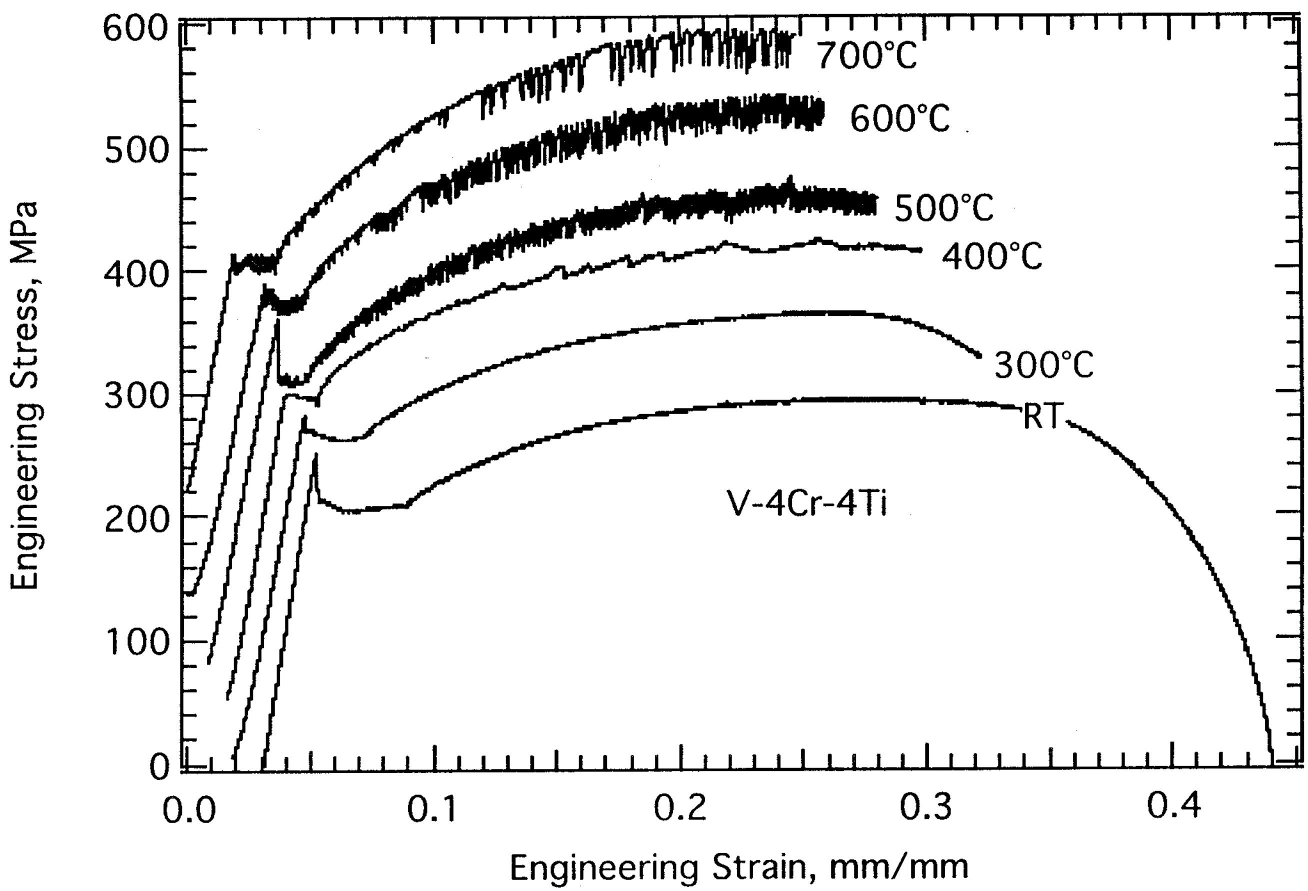
Dose Dependence of Radiation Hardening
in V-4Cr-4Ti Irradiated at Low Temperatures
Yield Strength (MPa)
Dose(dpa)
1000
900
800
700
600
500
400
300
200
0
10
20
30
40
50
T irr=300-330°C
T irr=400-430°C
Zinkle&Snead 1997
Billone et al 1997
Satou et al, 1996
vanOsch 1997
Snead&Zinkle 1997
Kazakov et al 1997

Total Elongation of Unirradiated and Irradiated V-4Cr-4Ti



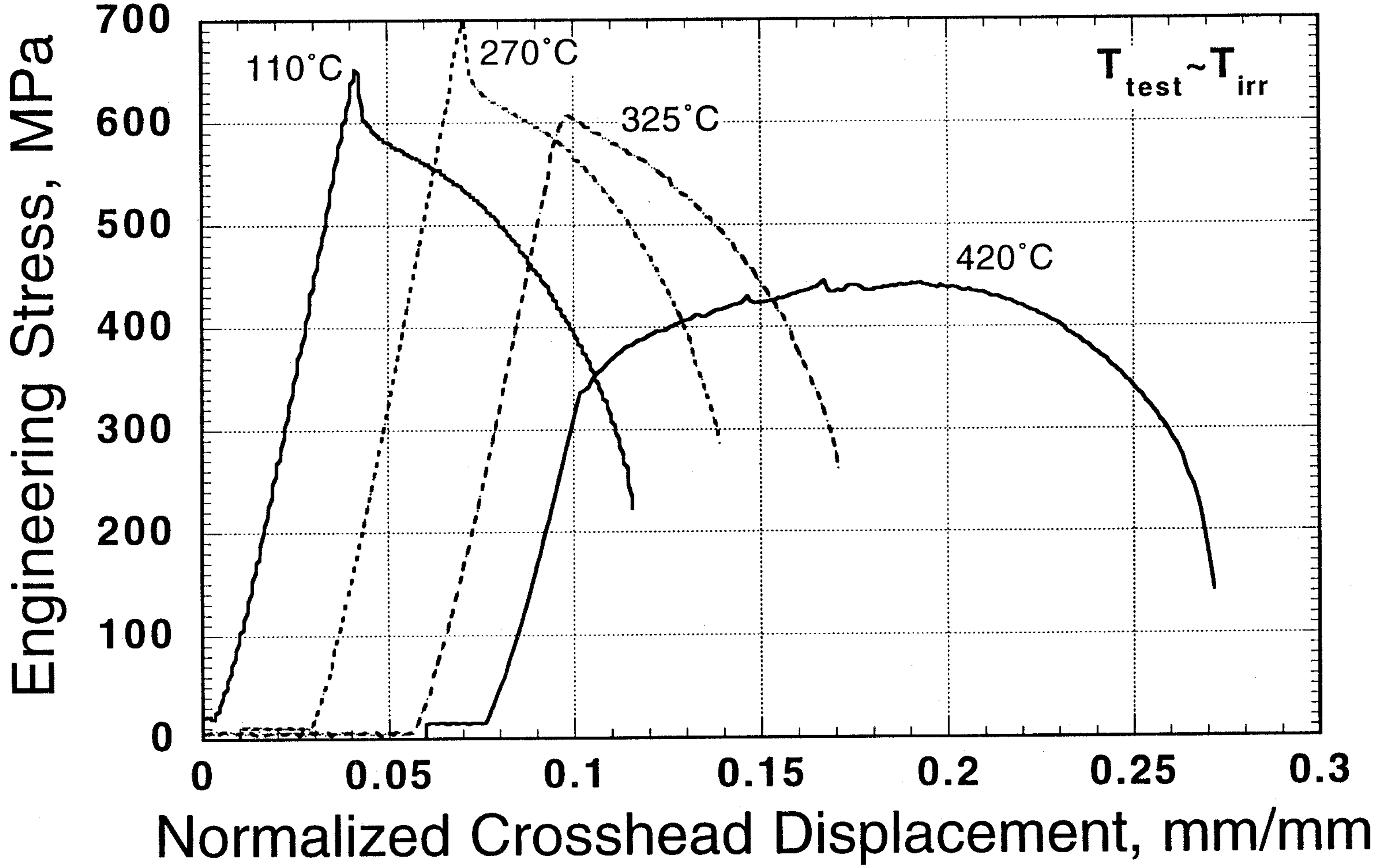
Effect of Irradiation on the Tensile Ductility of V-(4-5)%Cr-(4-5)%Ti Alloys



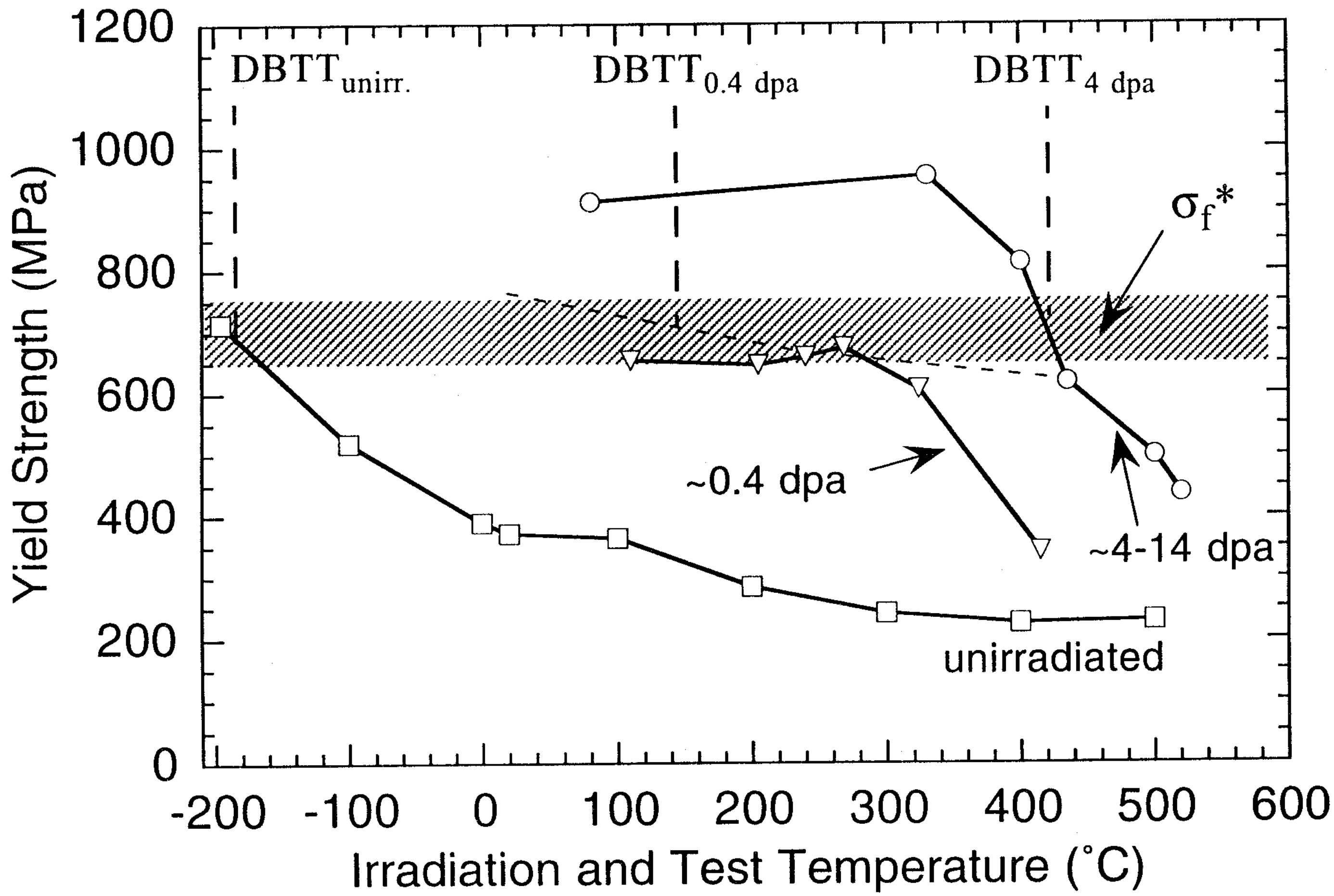


Engineering Stress, MPa
Engineering Strain, mm/mm
0
100
200
300
400
500
600
0.0
0.1
0.2
0.3
0.4
700°C
600°C
500°C
400°C
300°C
RT
V-4Cr-4Ti

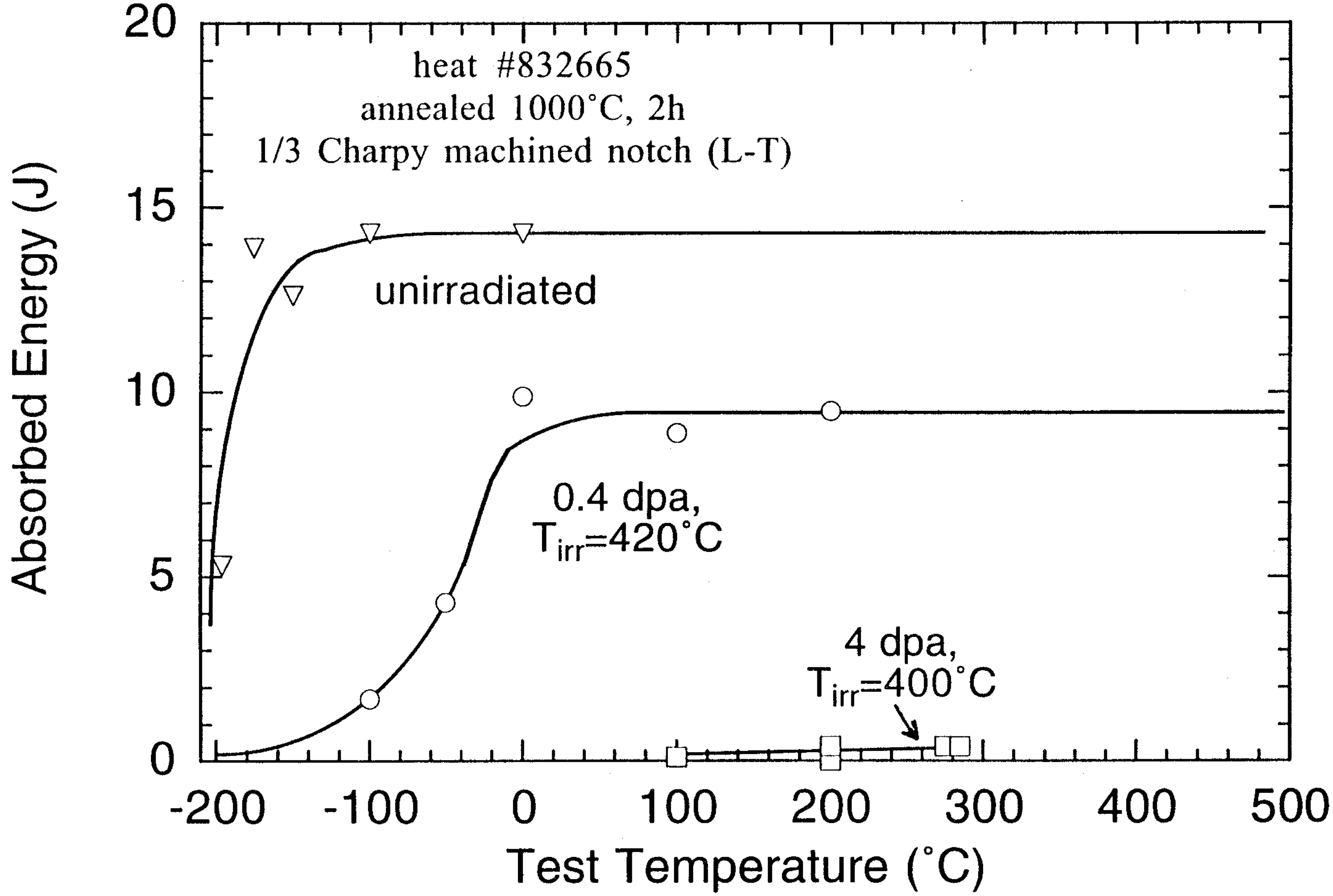
Load-Elongation Curves for V-4Cr-4Ti Irradiated in HFBR to 0.4 dpa



Low-Temperature Radiation Hardening Causes a Large Increase in the Ductile-to-Brittle-Transition Temperature in V-4%Cr-4%Ti Alloys



Effect of Neutron Irradiation at ~400˚C on the Charpy Impact Properties of V-4%Cr-4%Ti



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)

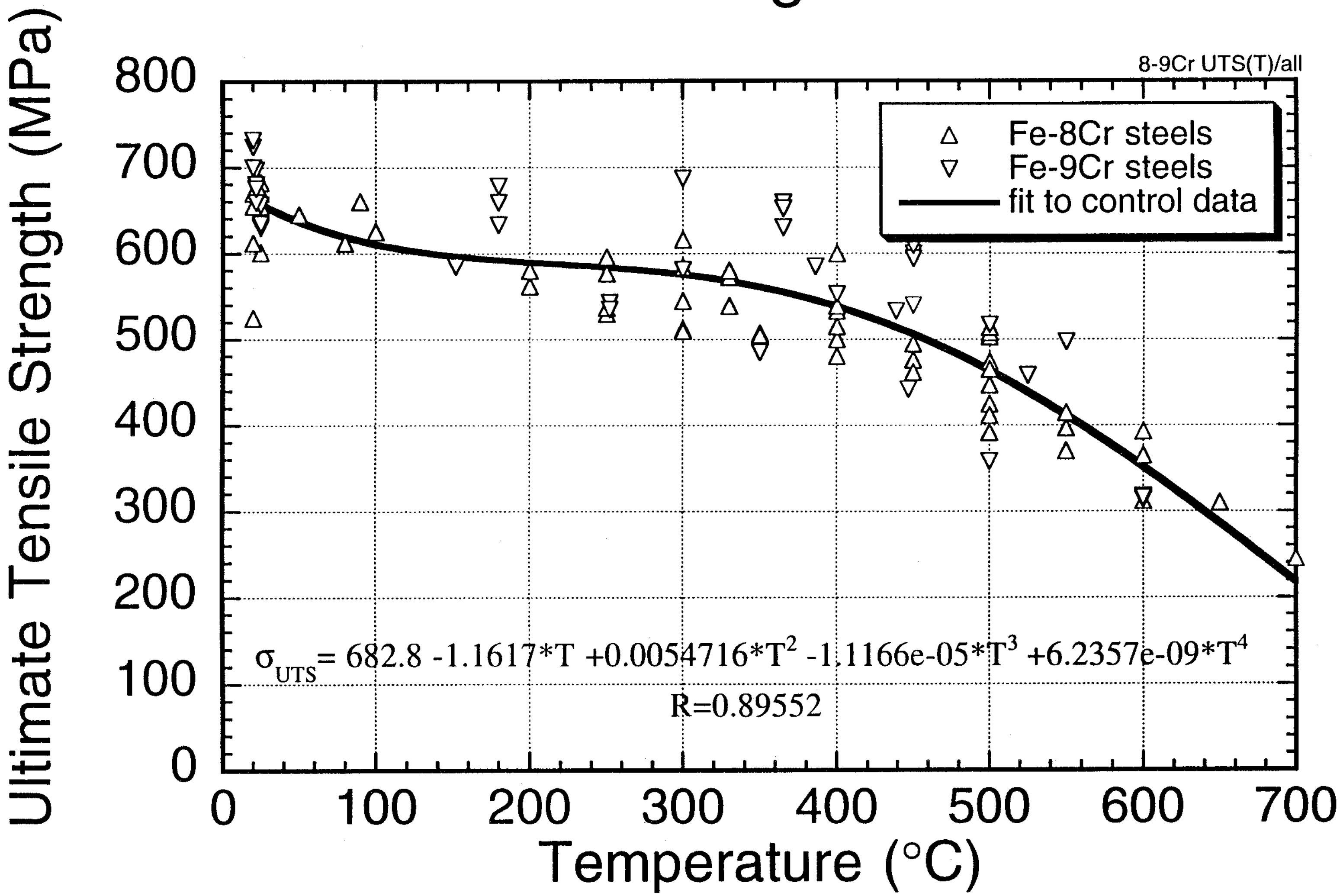
C_P = 0.5755 - 21.1 / T J/g-K (T in Kelvin)

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

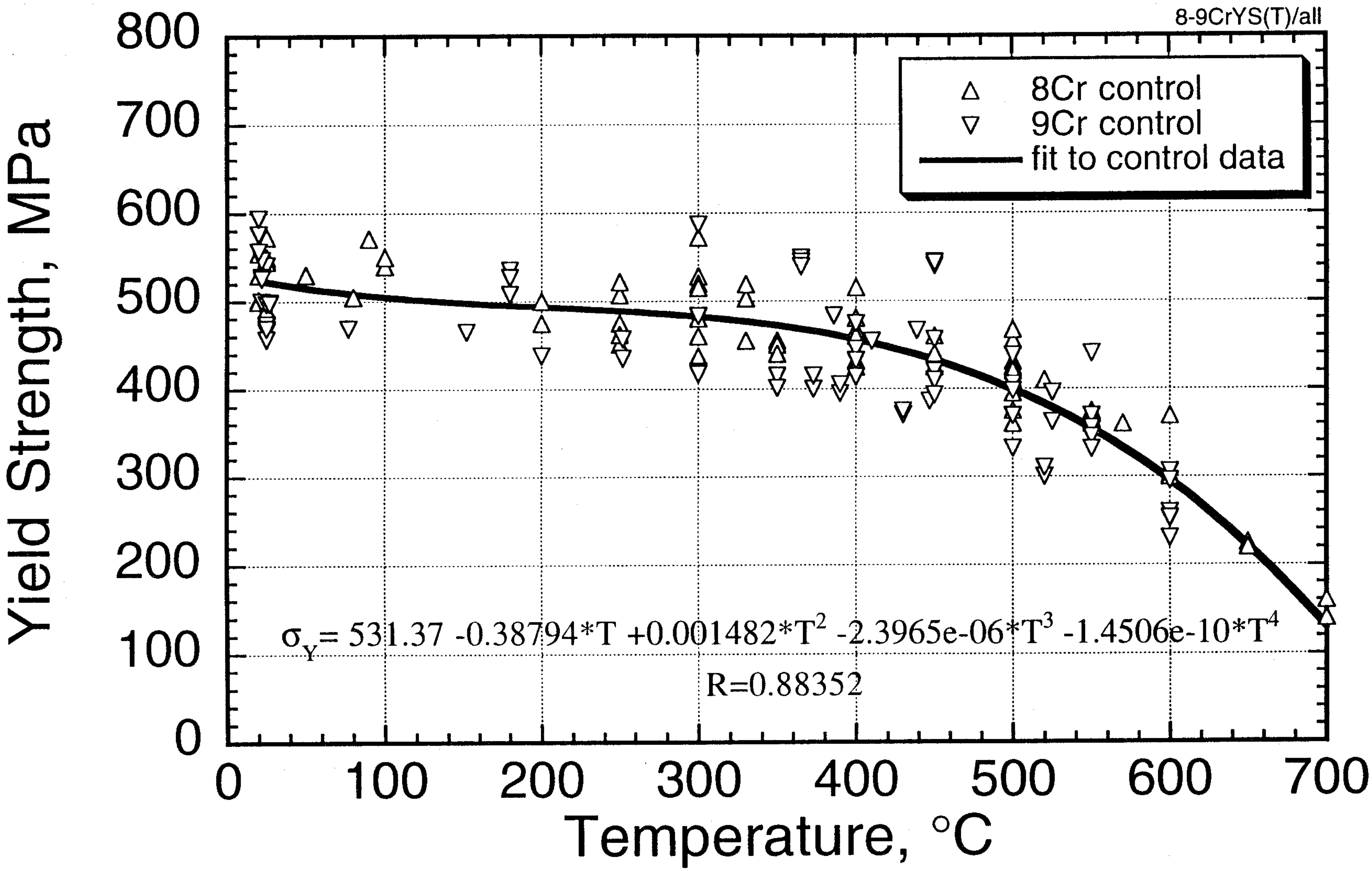
Recommended operating temperature limits (structural applications)

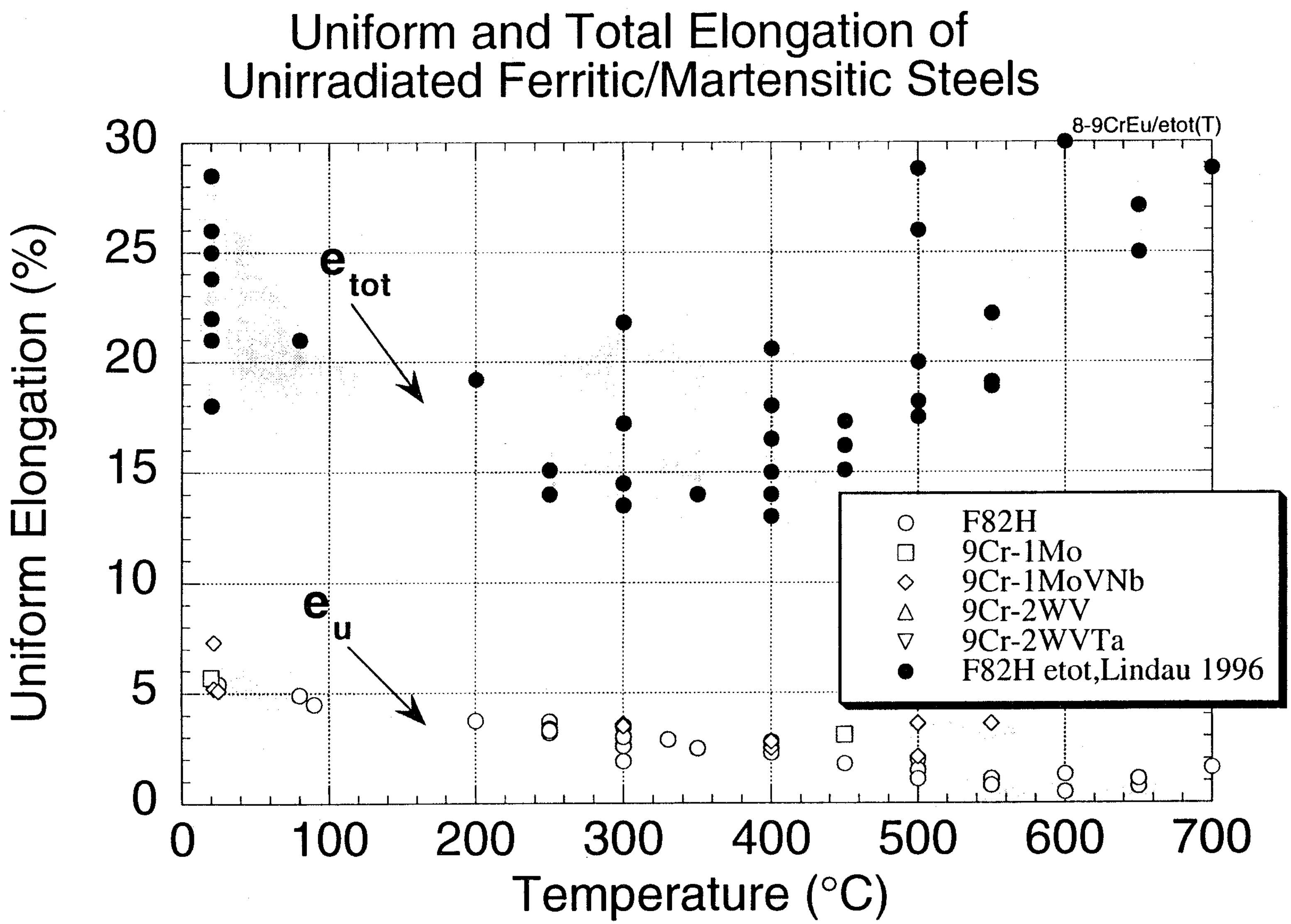
Tmin = 400°C (due to rad.-induced increase in DBTT at low T_{irr})
Tmax = 700°C (corrosion/chemical compatibility and thermal creep)

Ultimate Tensile Strength of 8-9Cr Steels



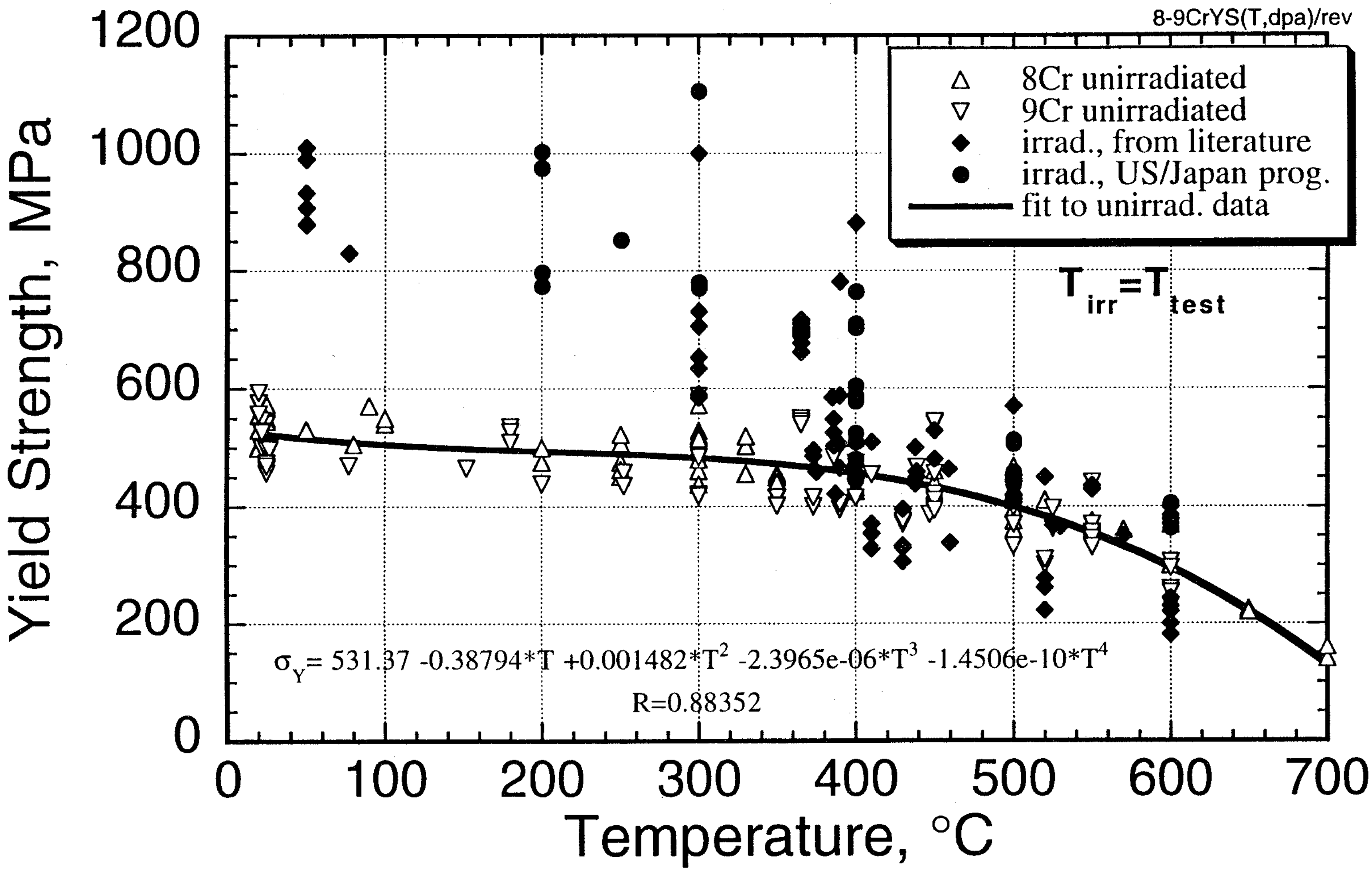
Yield Strength of 8-9Cr Steels



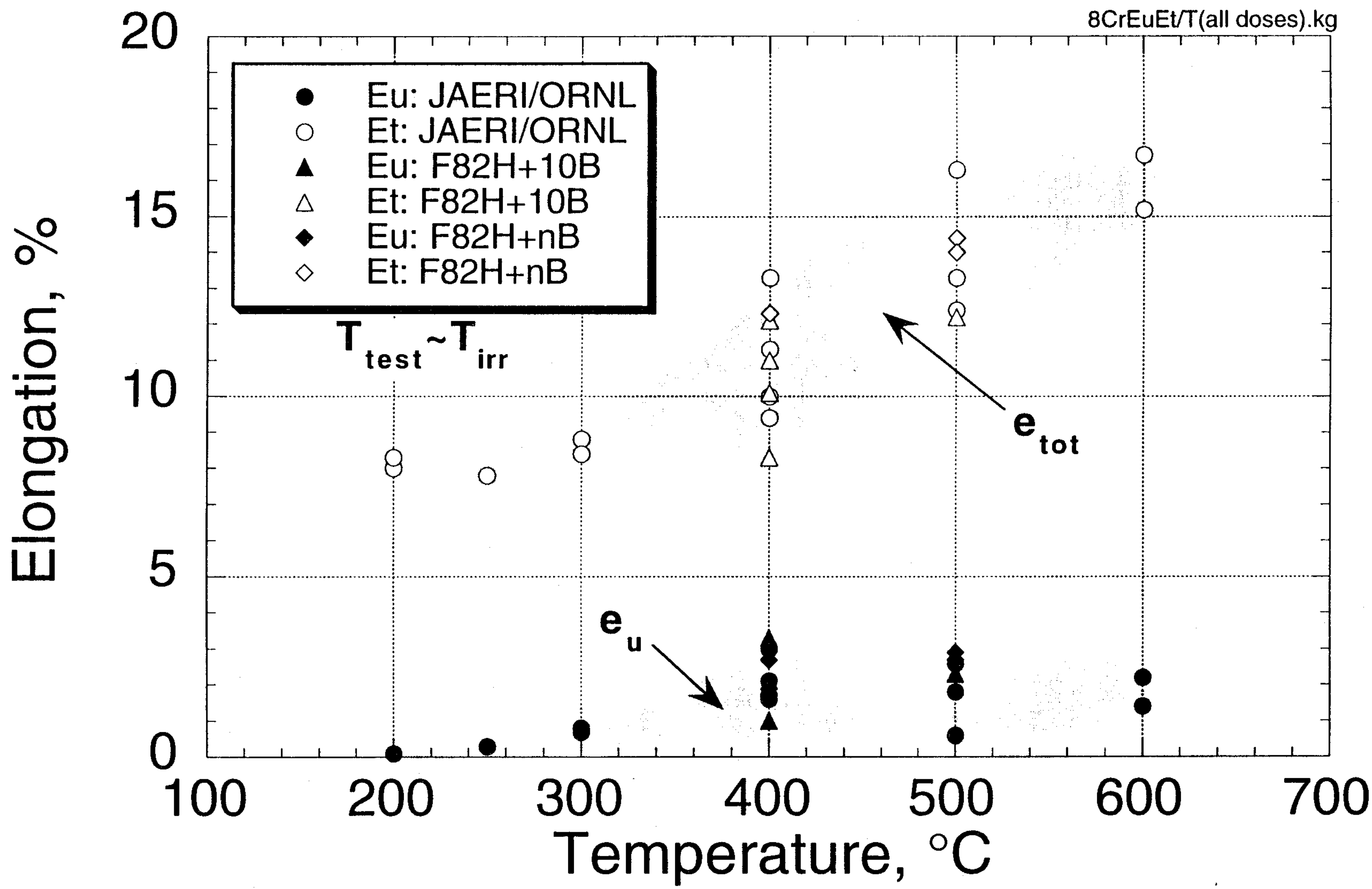


Uniform and Total Elongation of
Unirradiated Ferritic/Martensitic Steels
8-9CrEu/etot(T)
Uniform Elongation (%)
Temperature (°C)
e_{tot}
e_u
F82H
9Cr-1Mo
9Cr-1MoVNb
9Cr-2WV
9Cr-2WVTa
F82H etot,Lindau 1996
0
5
10
15
20
25
30
0
100
200
300
400
500
600
700

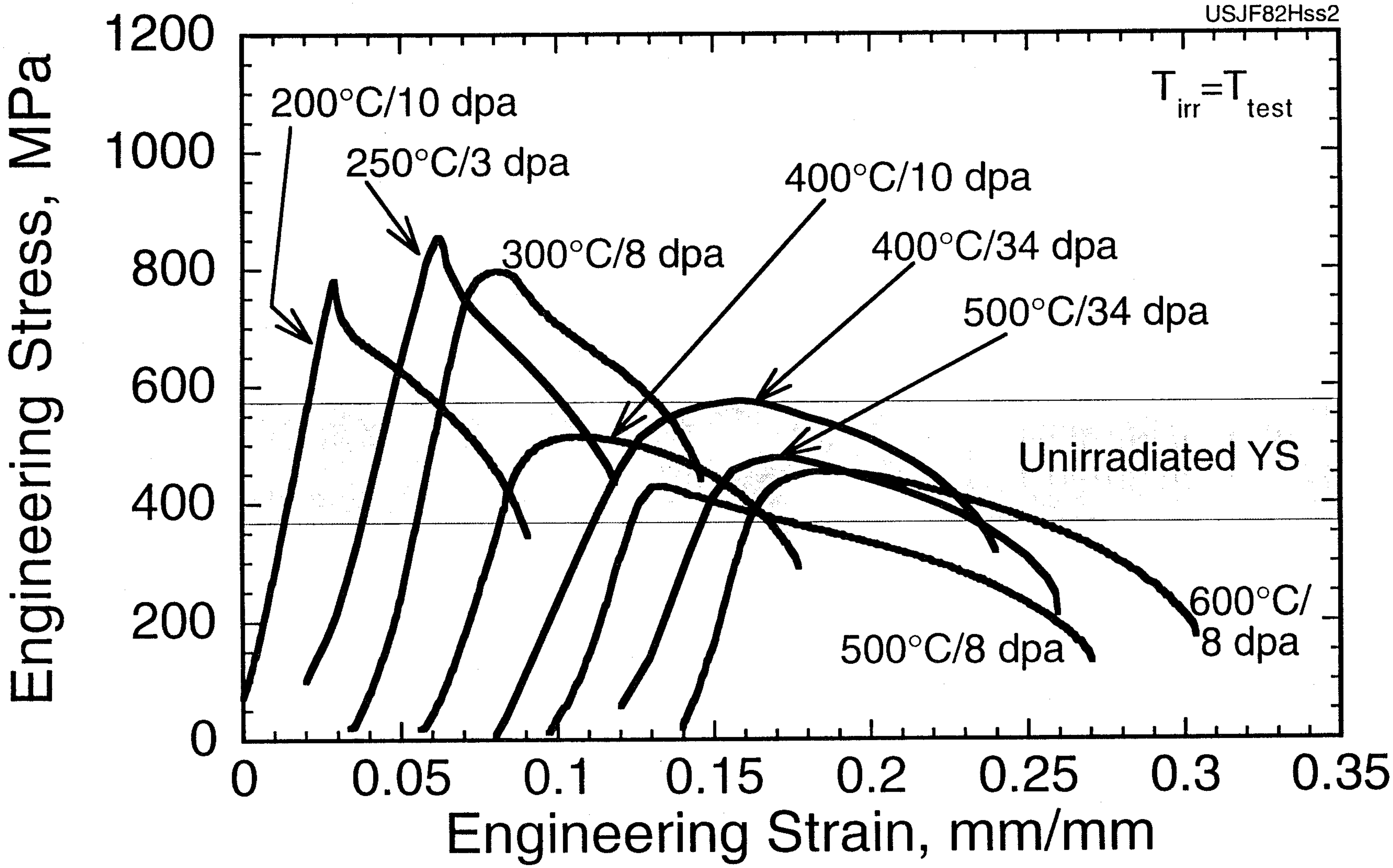
8-9Cr Steels: Yield Strength as Function of Temperature, 0.1 - 94 dpa

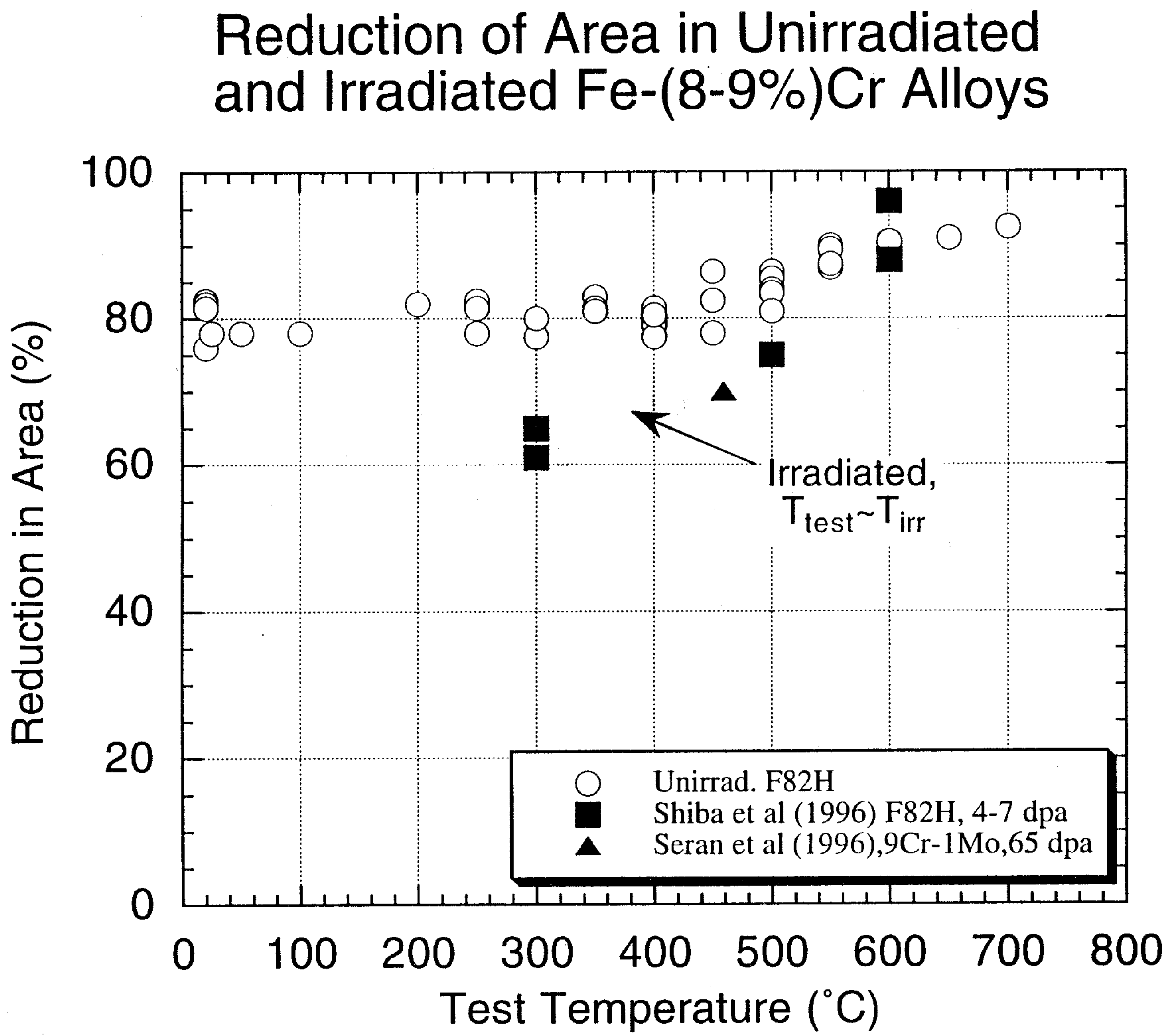


Uniform and Total Elongation in Irradiated Fe-8%Cr Steels



Representative USDOE/JAERI F82H Data: 200-600°C, 3-34 dpa

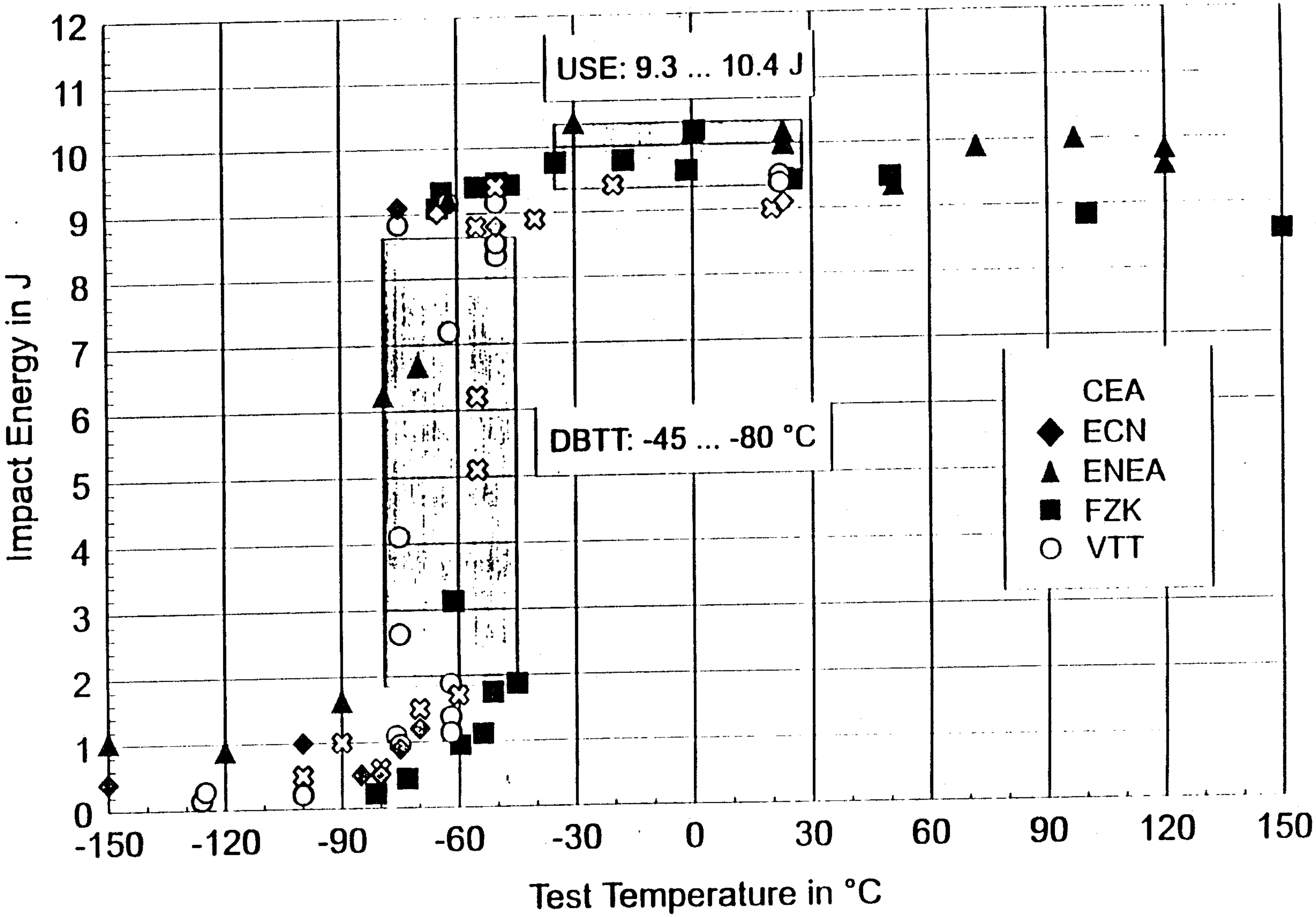




Reduction of Area in Unirradiated
and Irradiated Fe-(8-9%)Cr Alloys
Reduction in Area (%)
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
Test Temperature (˚C)
Irradiated,
$T_{test} \sim T_{irr}$
Unirrad. F82H
Shiba et al (1996) F82H, 4-7 dpa
Seran et al (1996),9Cr-1Mo,65 dpa

Forschung_zentrum Karlsruhe
Technik und Umwelt
Institut für Materialforschung II
Leiter: Prof. Dr. D. Munz

F82H

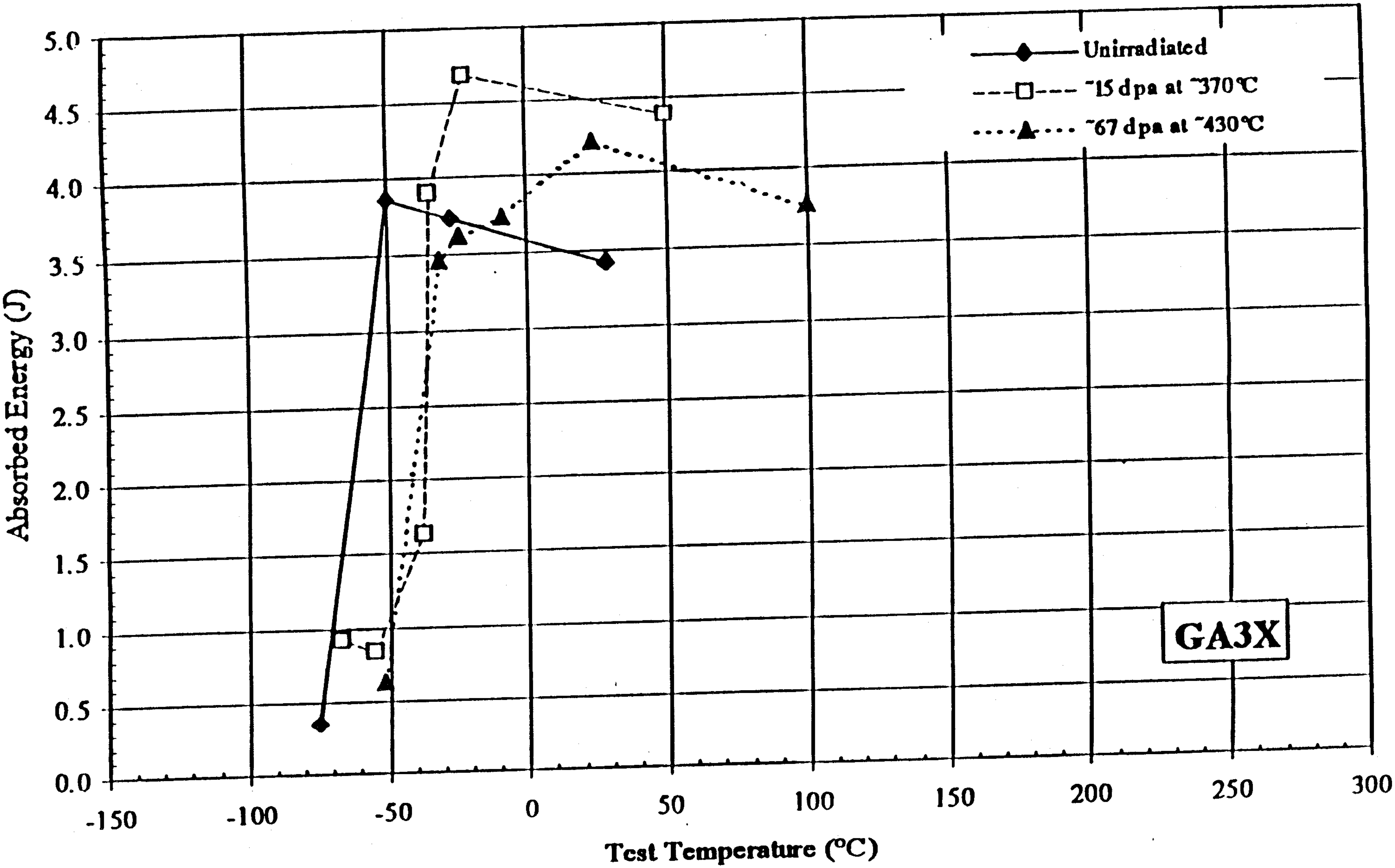


A. Alamo, G. Filacchioni, M. Horsten, M. Rieth, S. Tähtinen, Rev. 29.08.1996

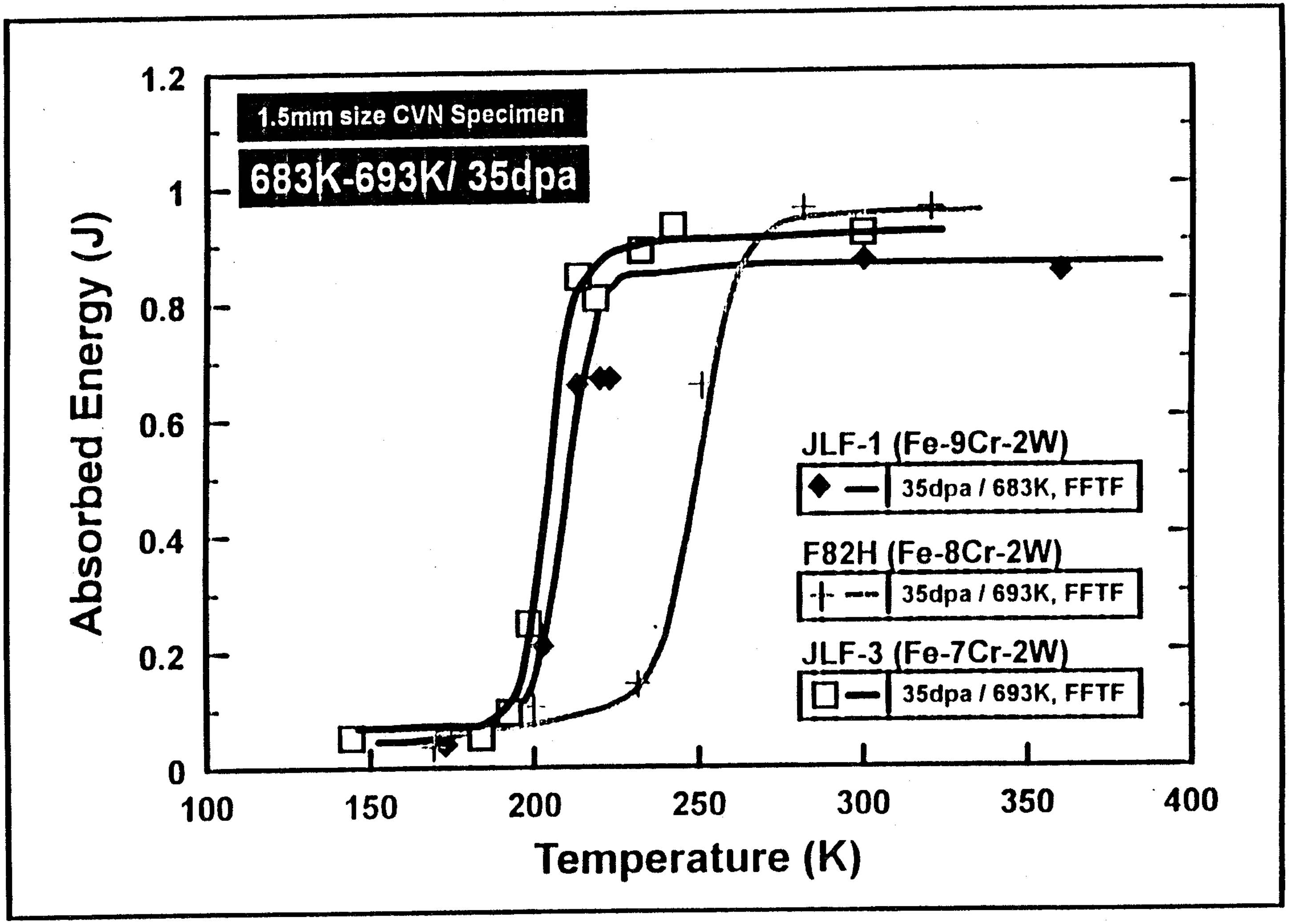
K. Ehrlich / R. Lindau (1996)

GA3X (Fe-9Cr-2W)

L.E. Schubert et al. (1996)

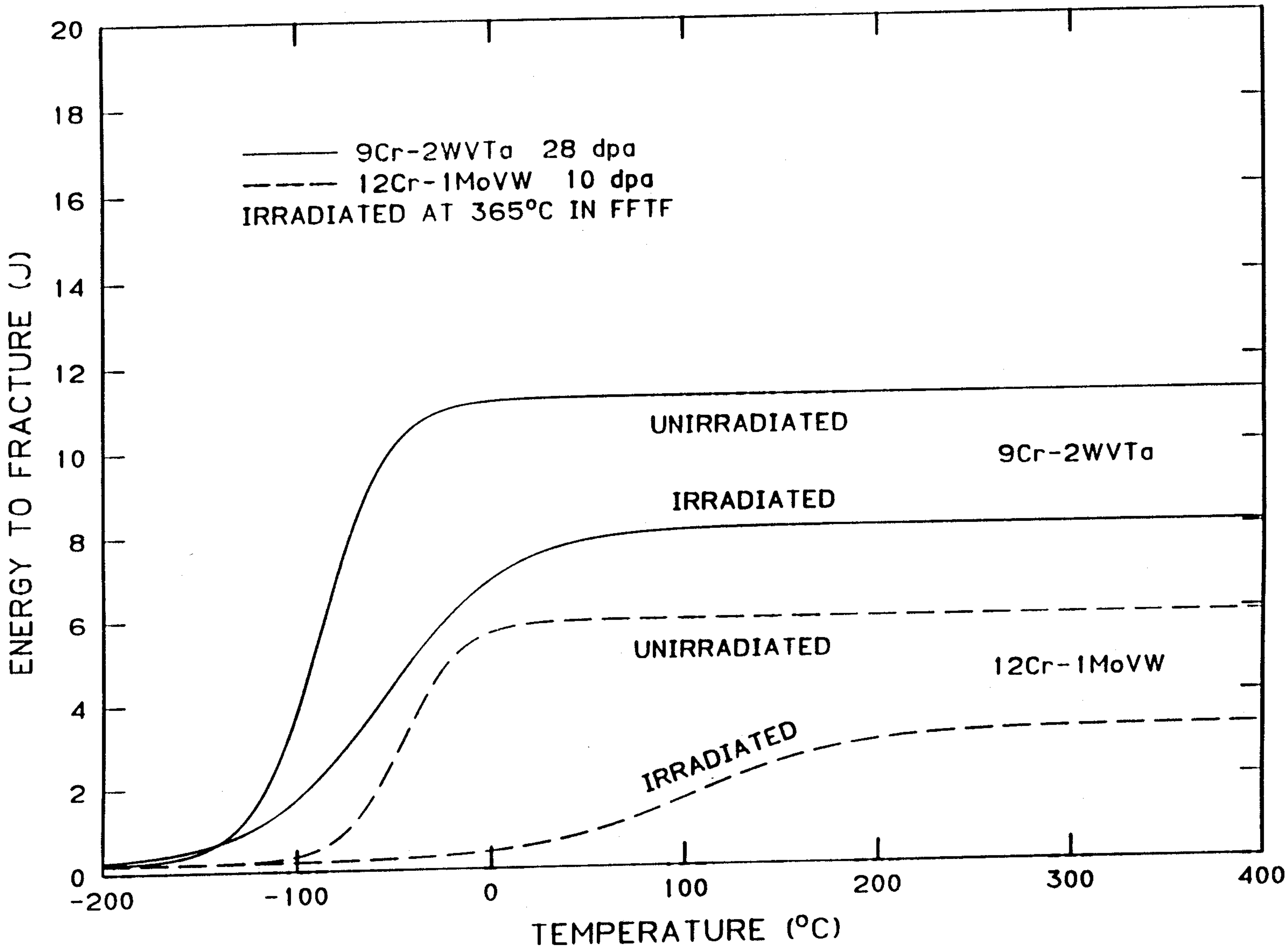


Charpy Impact Test Results / 1.5mm CVN
= JLF-1, F82H, JLF-3 =
(683K-693K: 35dpa)



A. Kohyama (1996)

9CR-2WVTa IS IMPROVEMENT OVER CONVENTIONAL STEELS



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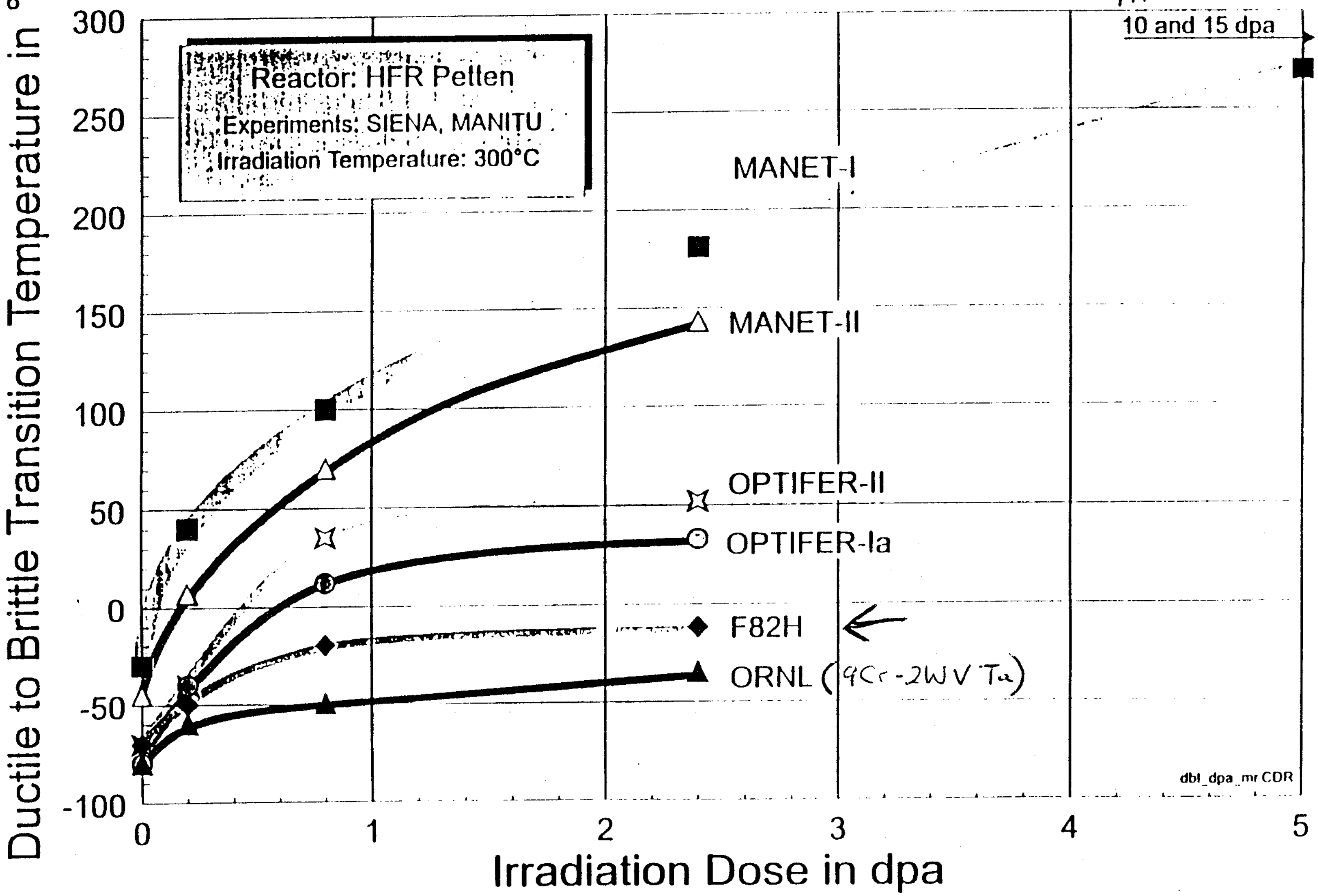
$T_{irr} = 300°C$



M. Rieth, Irradiation project manitu 300°C, Rev. 30.08.1996

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?

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=0.20

Thermophysical properties

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

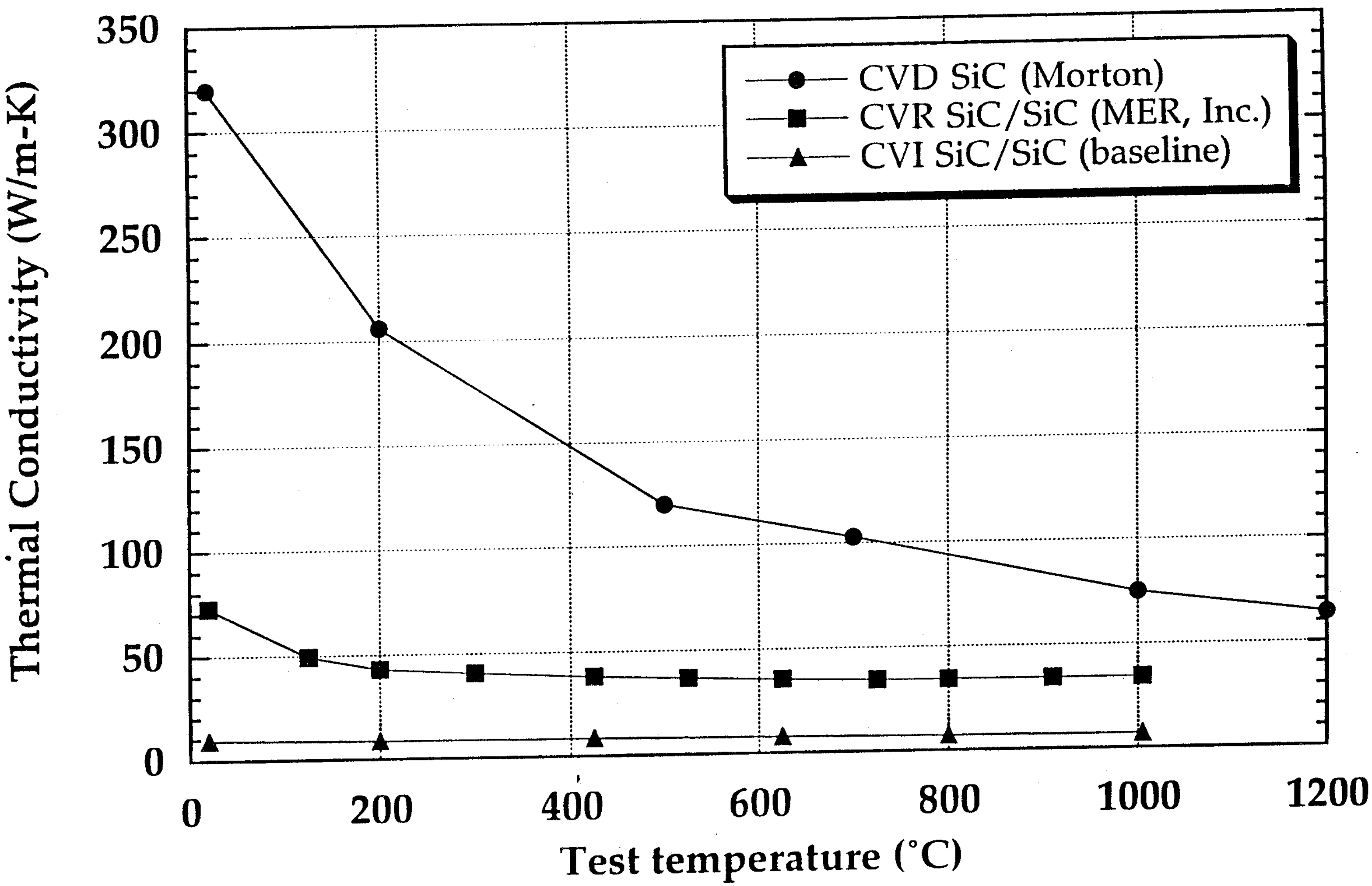
C_P = 1.13 J/g-K (500°C) to 1.22 J/g-K (1000°C)

k_{th} = 12.5-10 W/m-K (400-1000°C, after irradiation at 1000°C)

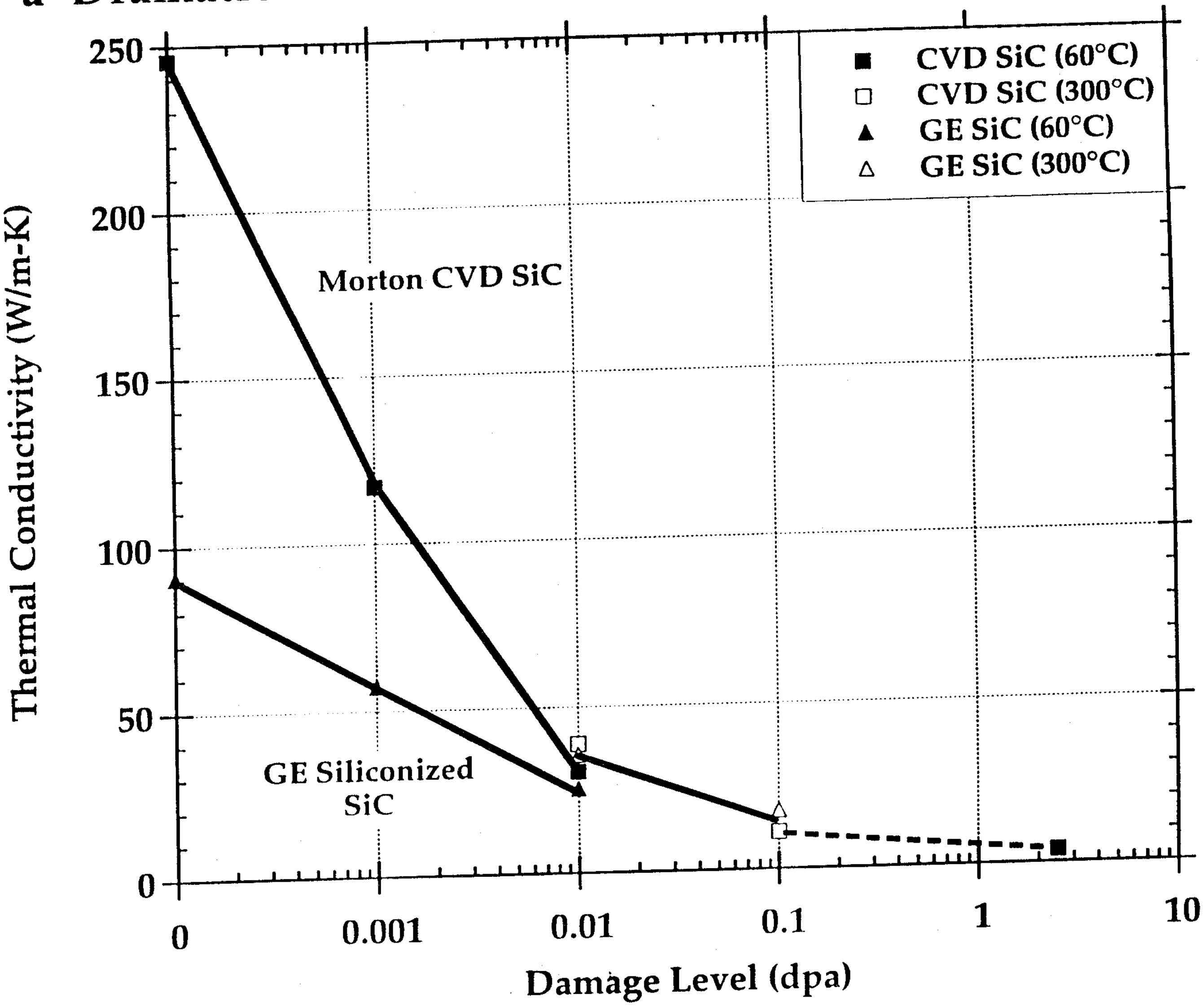
Recommended operating temperature limits (structural applications)

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

Large Improvements in the Thermal Conductivity of SiC have been Achieved in the Past Five Years



Low-Temperature Neutron Irradiation Causes a Dramatic Decrease in SiC Thermal Conductivity

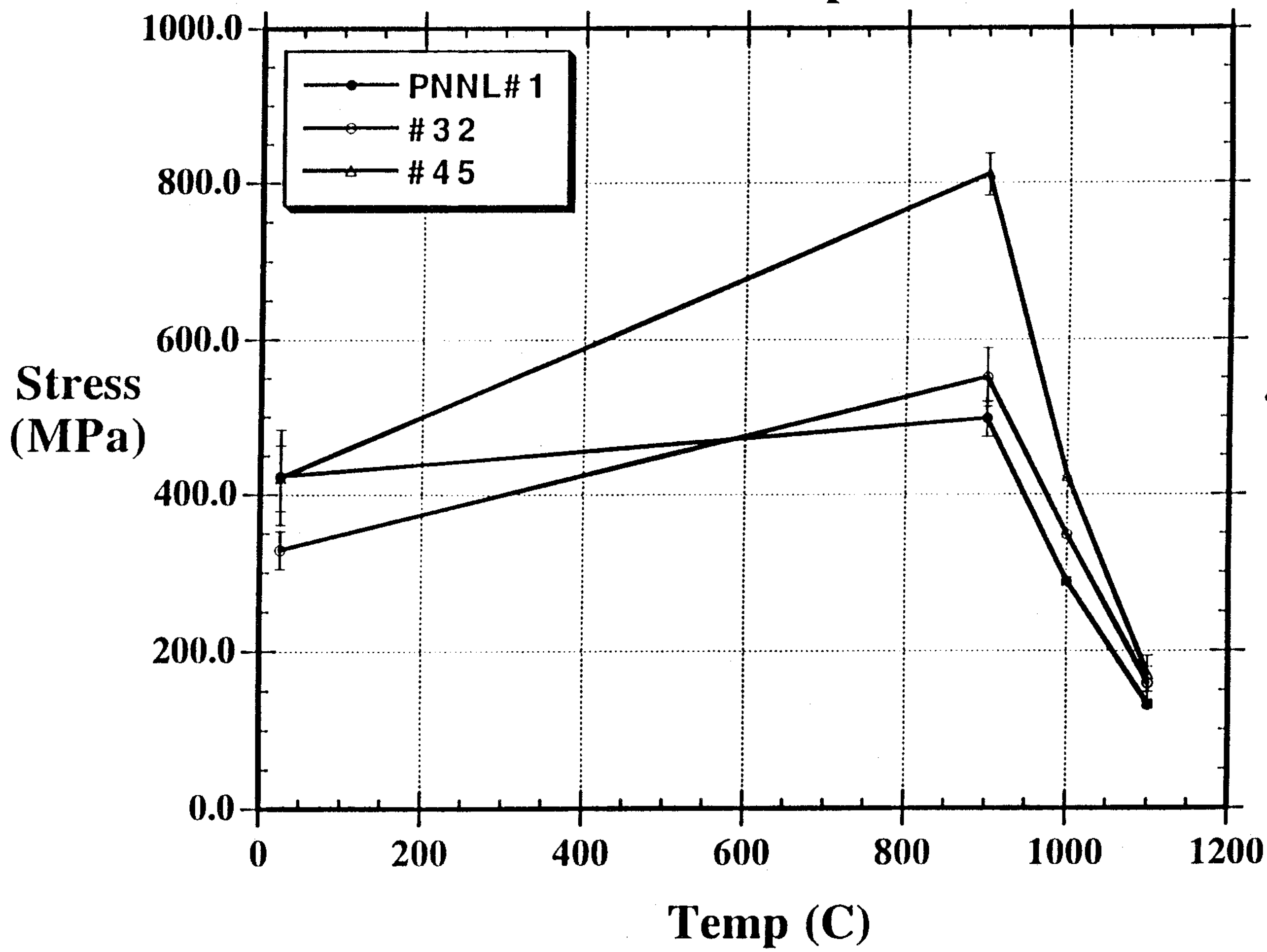


L.L. Snead, S.J. Zinkle, D.P. White
J. Nucl. Mater. (1997) in press

Quest Inc. / PNNL unpublished data (STTR project)

Ti_3SiC_2/SiC Composite Bend Strength

as a function of test temperature in air.



Ti_3SiC_2 properties

$T_M > 3000°C$
$E = 326$ GPa
$\alpha_{th} = 10$ ppm/°C
$K_{th} = 43$ W/m-K @ RT
$\sigma_e = 4.5 \times 10^6$ S/m @ RT (~8% IACS)

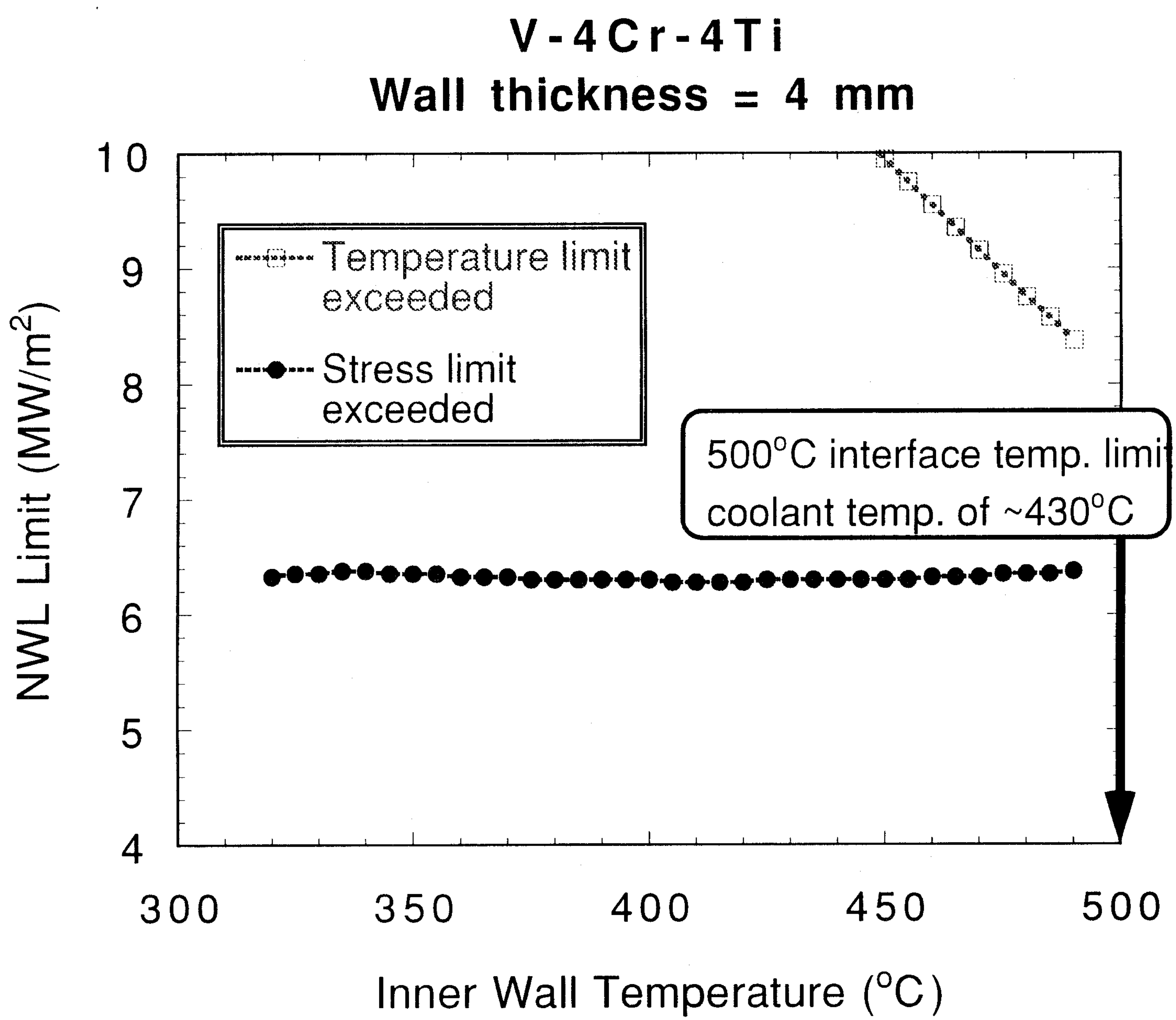
brittle at RT; "slight ductility" at elevated T

$K_{Ic} \sim 9$ MPa $\sqrt{m}$.

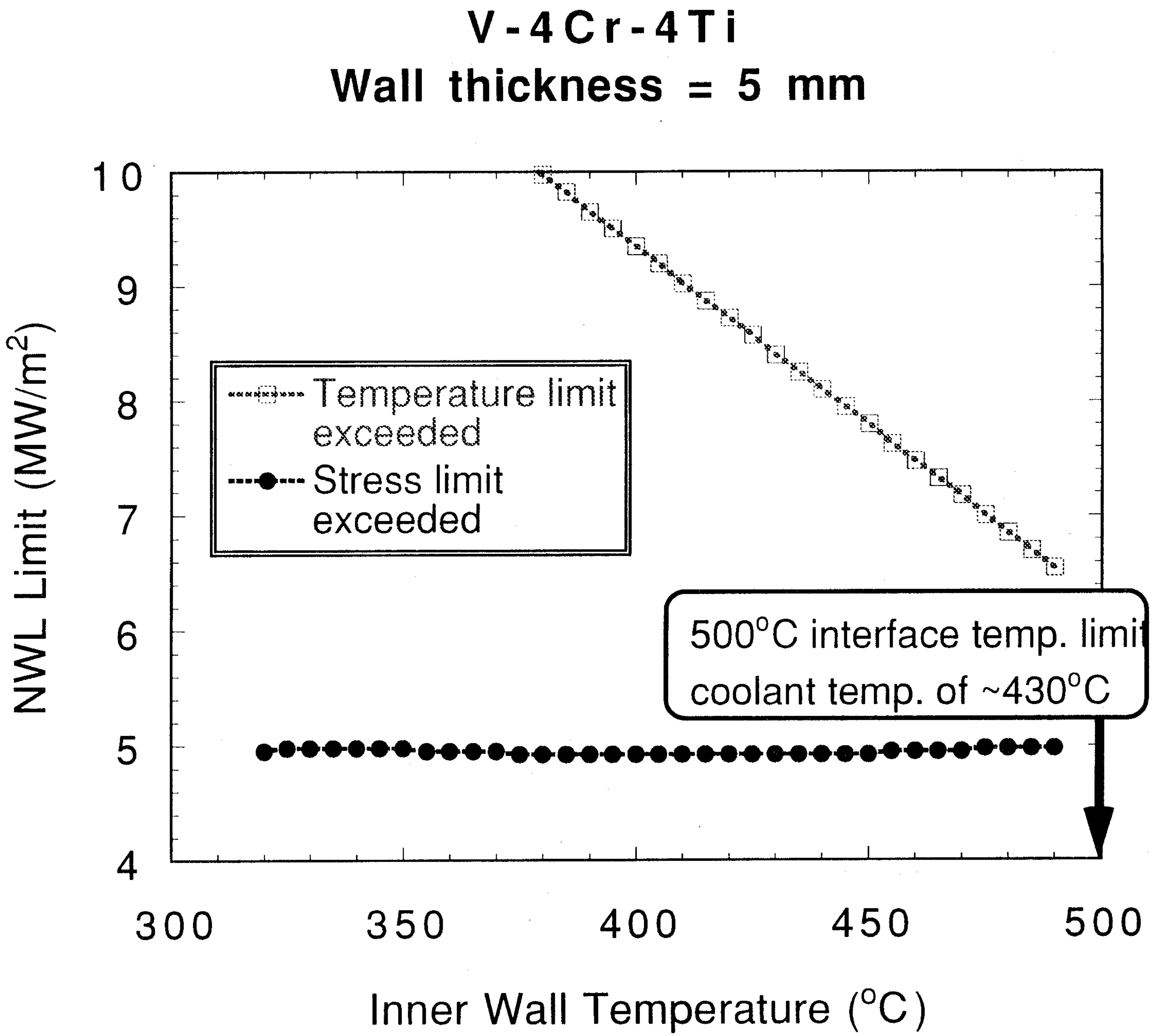
cf. Barsoum + El-Raghy J. Am. Cer. Soc. 79, 7 (1996) 1953

Radhakrishnan et al. Scripta Mater. 34, 12 (1996) 1809

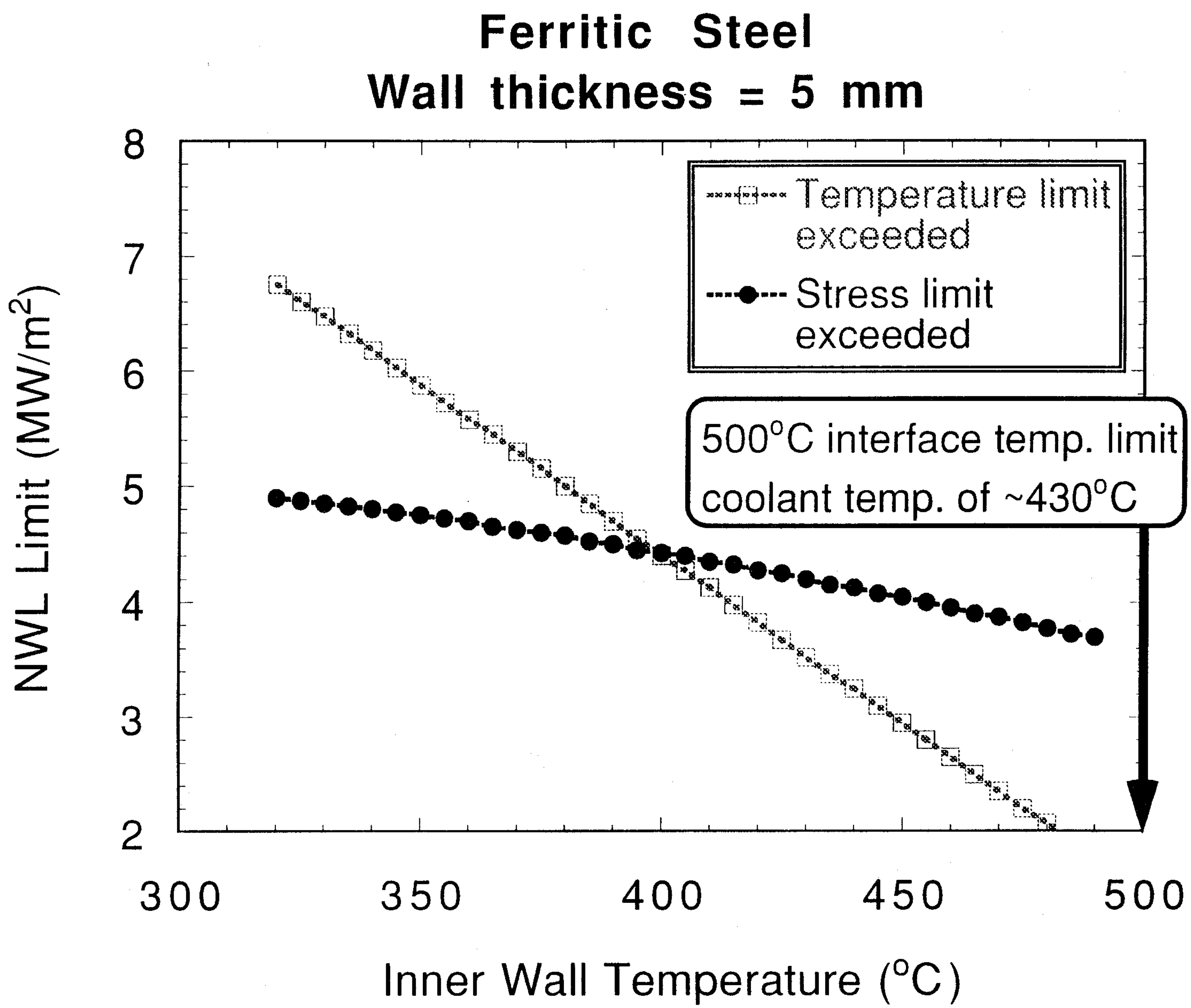
Quest, Inc. / PNNL unpublished data (1997)



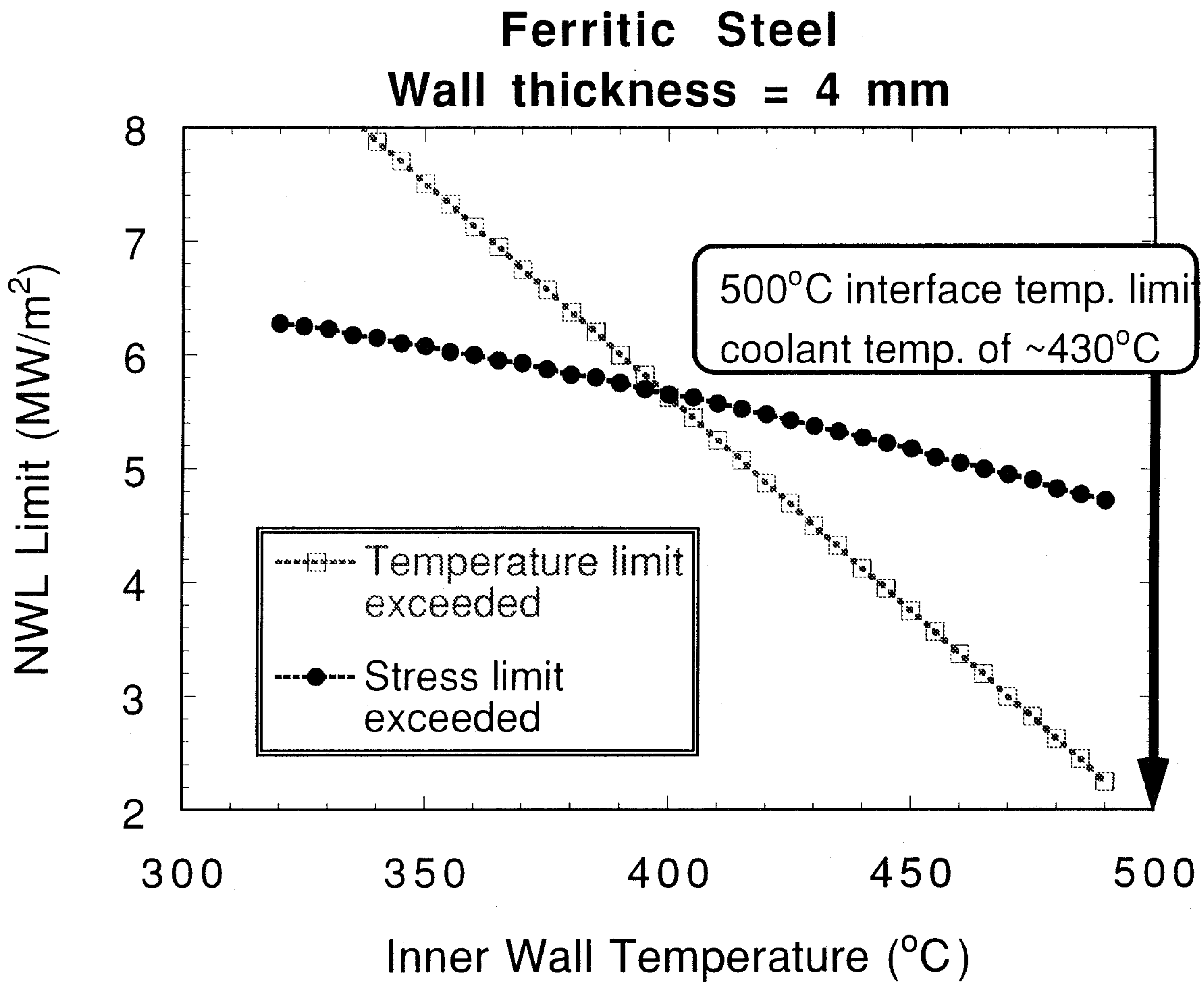
V-4Cr-4Ti
Wall thickness = 4 mm
Temperature limit exceeded
Stress limit exceeded
500°C interface temp. limit
coolant temp. of ~430°C
NWL Limit (MW/m2)
Inner Wall Temperature (°C)
10
9
8
7
6
5
4
300
350
400
450
500



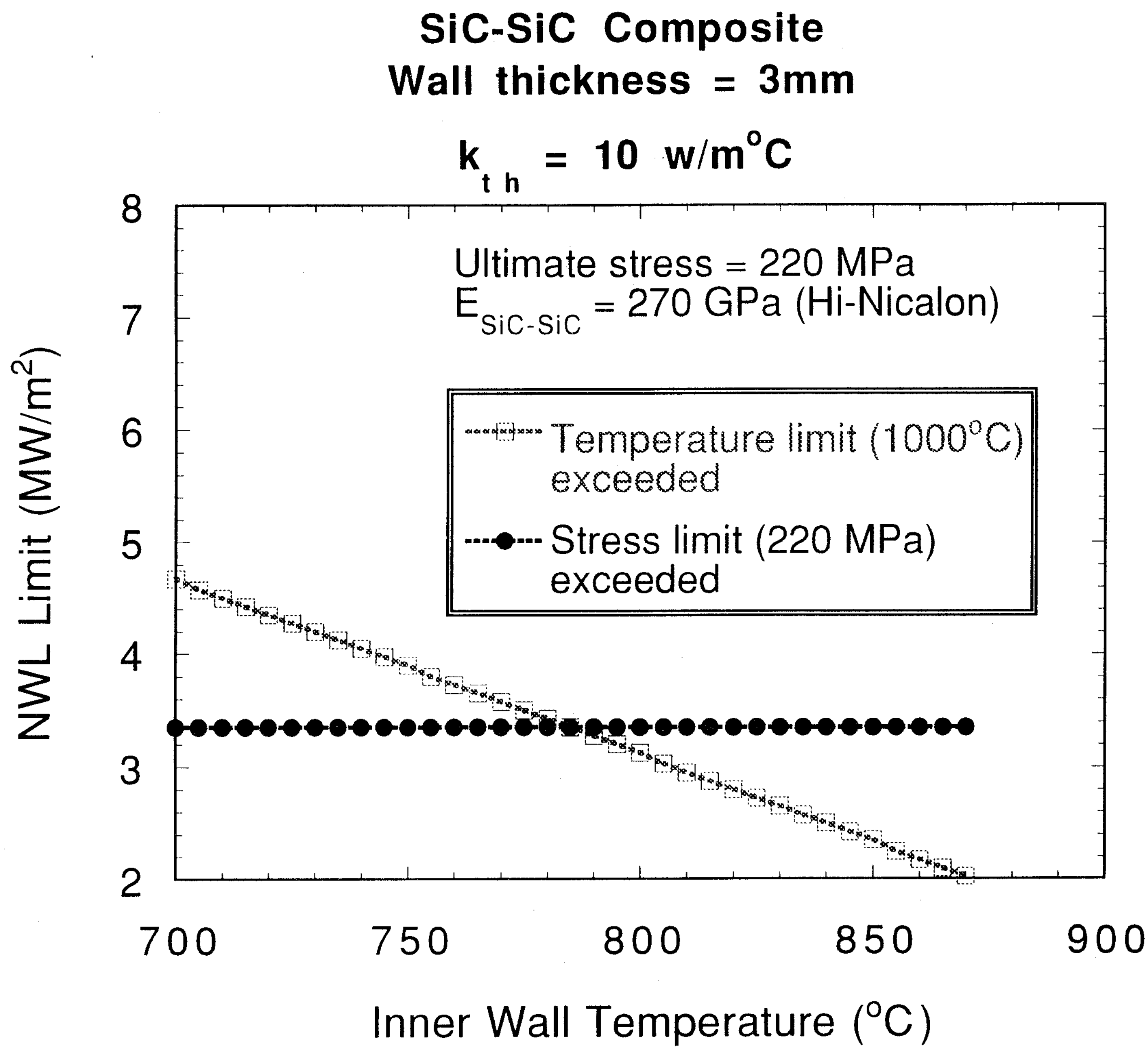
V-4Cr-4Ti
Wall thickness = 5 mm
NWL Limit (MW/m2)
Inner Wall Temperature (oC)
Temperature limit exceeded
Stress limit exceeded
500oC interface temp. limit
coolant temp. of ~430oC
10
9
8
7
6
5
4
300
350
400
450
500

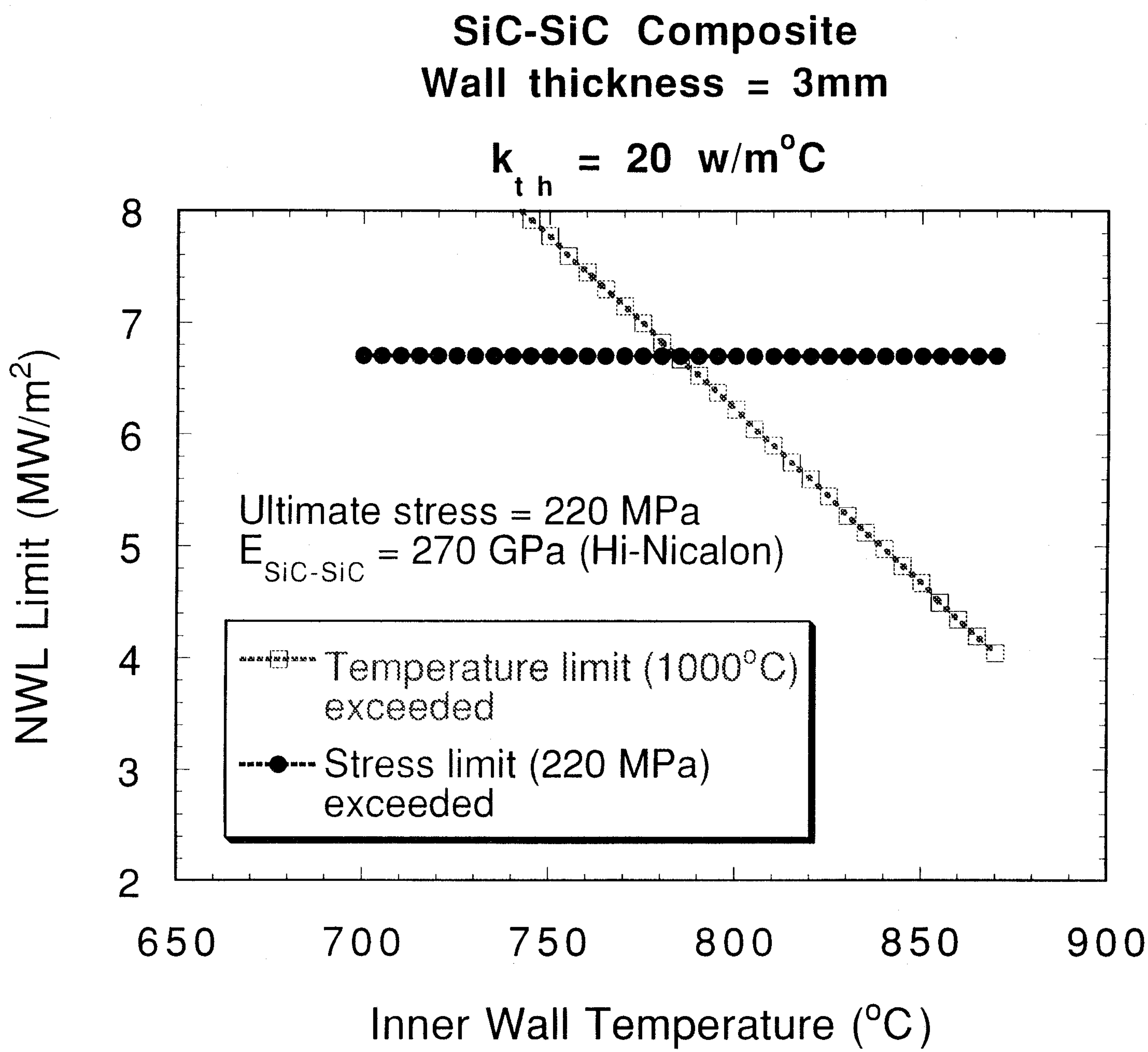


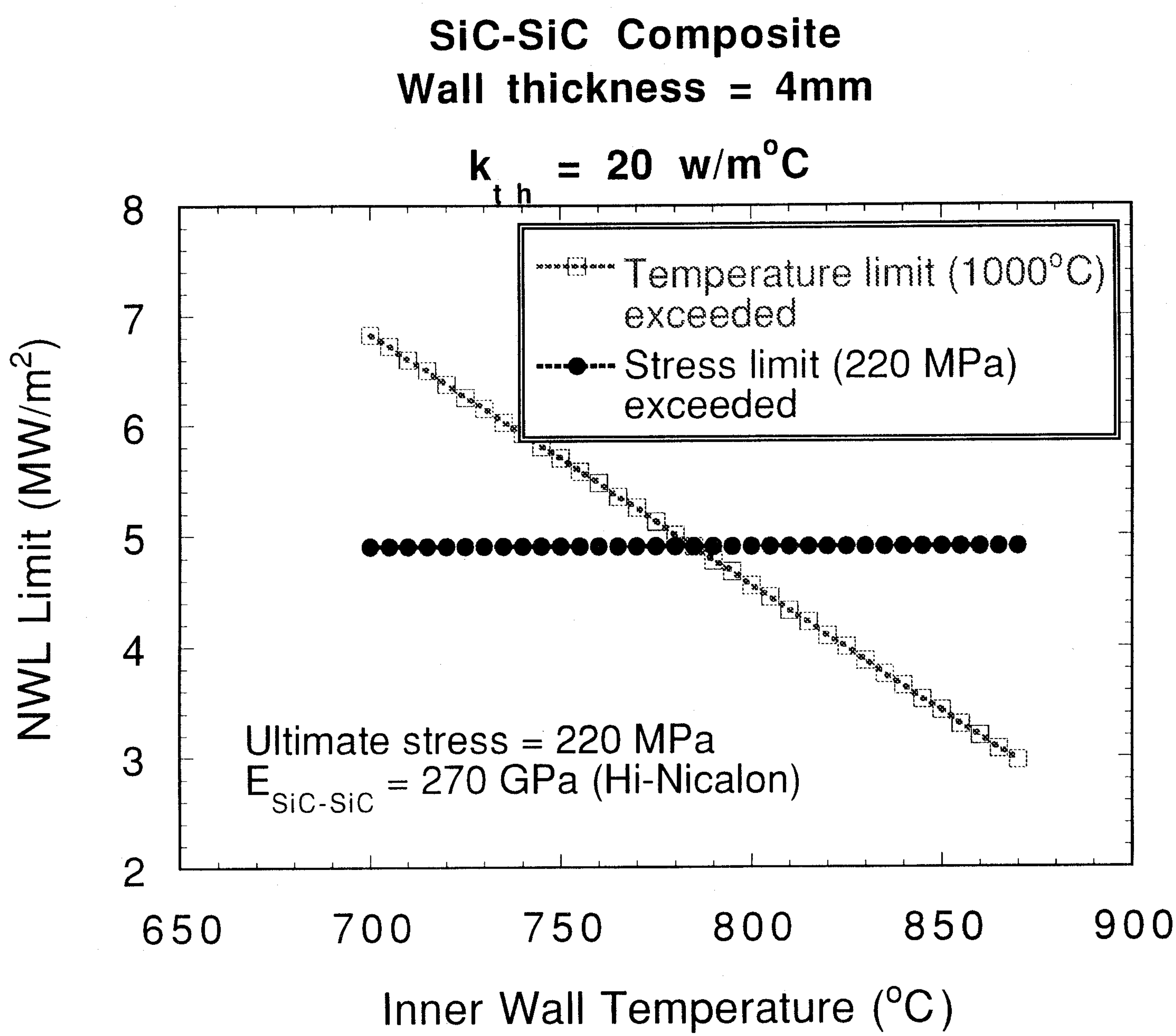
Ferritic Steel
Wall thickness = 5 mm
Temperature limit exceeded
Stress limit exceeded
500°C interface temp. limit
coolant temp. of ~430°C
NWL Limit (MW/m2)
Inner Wall Temperature (°C)
8
7
6
5
4
3
2
300
350
400
450
500



Ferritic Steel
Wall thickness = 4 mm
500°C interface temp. limit
coolant temp. of ~430°C
Temperature limit exceeded
Stress limit exceeded
NWL Limit (MW/m²)
Inner Wall Temperature (°C)
8
7
6
5
4
3
2
300
350
400
450
500

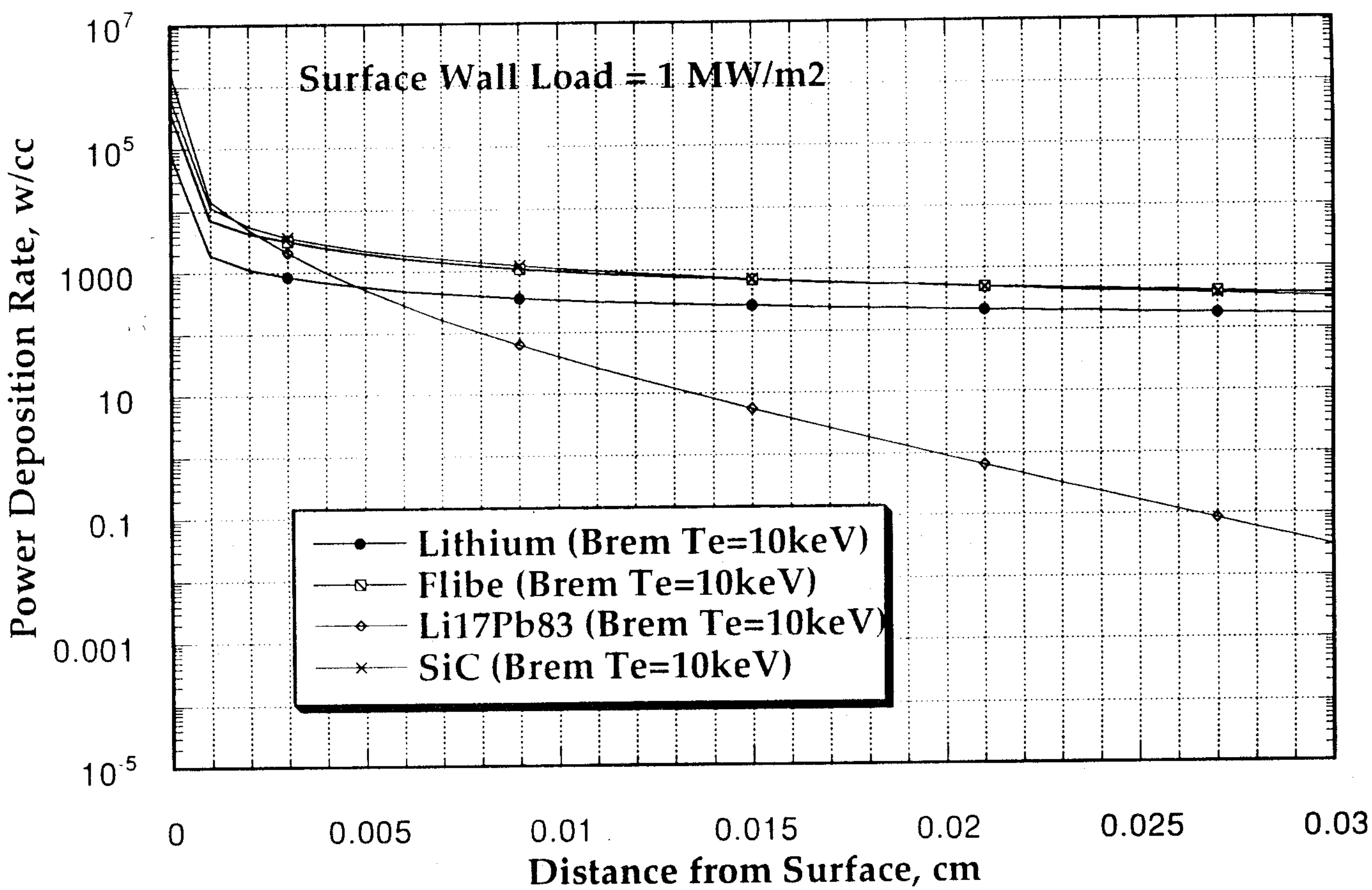

SiC-SiC Composite
Wall thickness = 3mm
k_{th} = 10 w/m°C
Ultimate stress = 220 MPa
$E_{SiC-SiC}$ = 270 GPa (Hi-Nicalon)
Temperature limit (1000°C) exceeded
Stress limit (220 MPa) exceeded
NWL Limit (MW/m²)
8
7
6
5
4
3
2
700
750
800
850
900
Inner Wall Temperature (°C)

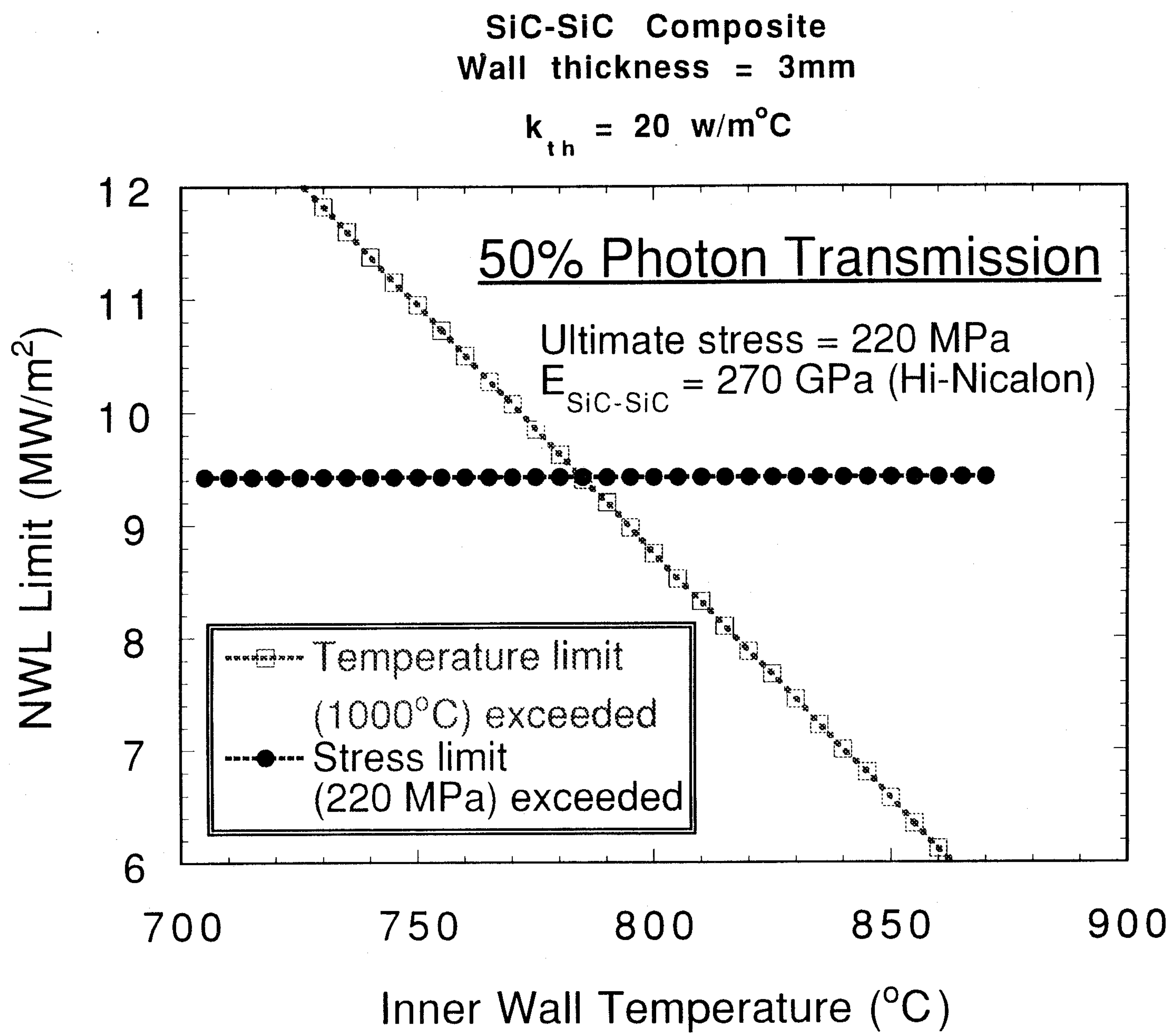

SiC-SiC Composite
Wall thickness = 3mm
k_{th} = 20 w/m°C
NWL Limit (MW/m^2)
Inner Wall Temperature (°C)
8
7
6
5
4
3
2
650
700
750
800
850
900
Ultimate stress = 220 MPa
$E_{SiC-SiC}$ = 270 GPa (Hi-Nicalon)
Temperature limit (1000°C) exceeded
Stress limit (220 MPa) exceeded



SiC-SiC Composite
Wall thickness = 4mm
k_{th} = 20 w/m°C
Temperature limit (1000°C) exceeded
Stress limit (220 MPa) exceeded
Ultimate stress = 220 MPa
$E_{SiC-SiC}$ = 270 GPa (Hi-Nicalon)
NWL Limit (MW/m^2)
Inner Wall Temperature (°C)
2
3
4
5
6
7
8
650
700
750
800
850
900

Comparison of Classical Bremsstrahlung Radiation Incident on Several Materials





SiC-SiC Composite
Wall thickness = 3mm
k th = 20 w/m°C
50% Photon Transmission
Ultimate stress = 220 MPa
E SiC-SiC = 270 GPa (Hi-Nicalon)
Temperature limit (1000°C) exceeded
Stress limit (220 MPa) exceeded
NWL Limit (MW/m2)
Inner Wall Temperature (°C)
12
11
10
9
8
7
6
700
750
800
850
900