The Status of Studies on Structural Materials under High Energy Proton and Neutron Mixed Spectrum

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Outline

- Introduction
- Irradiation experiments in spallation targets
- Representative results of austenitic and martensitic steels
- Summary and Outlook

Introduction

Introduction

High power spallation targets

Spallation Source	Power (MW)	Proton energy (GeV)	Target materials	Main structural materials	Annual damage rate ** (dpa in Fe)
SINQ (CW)	0.75 (~ 1)*	0.56	Pb	Zry-2 SS 316L Al-alloy	~20
SNS (pulsed)	0.7 (1.4)*	1.0	Hg	SS 316L	~20
JSNS (pulsed)	0.1 (1.0)*	3.0	Hg	SS 316L	~20
Spallation targets in ADS (CW)	> 5(?)	~1.0	Pb or PbBi	T91 SS 316 ODS steels	> 50

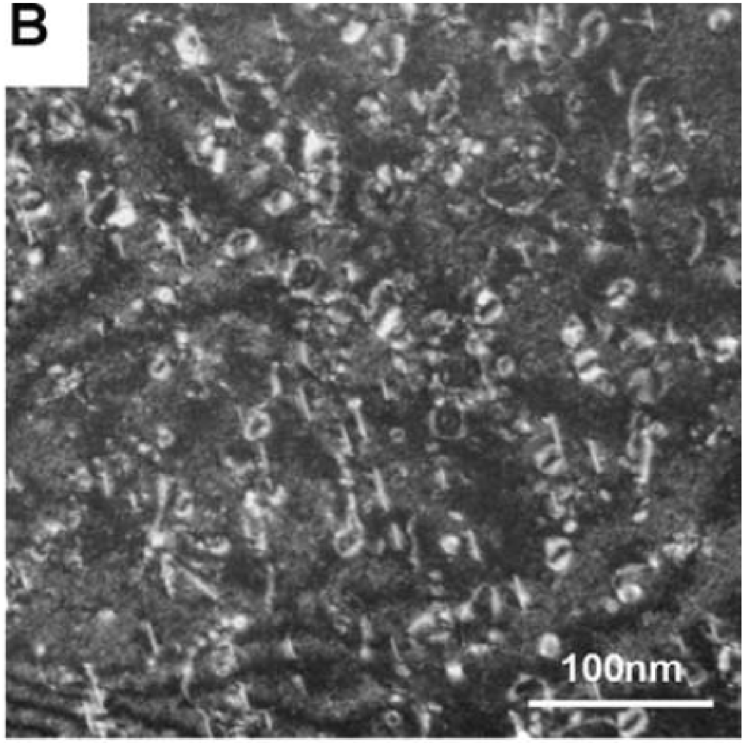
* Maximum power to be reached

** at beam window position, at the maximum power and for a full operation year

Introduction

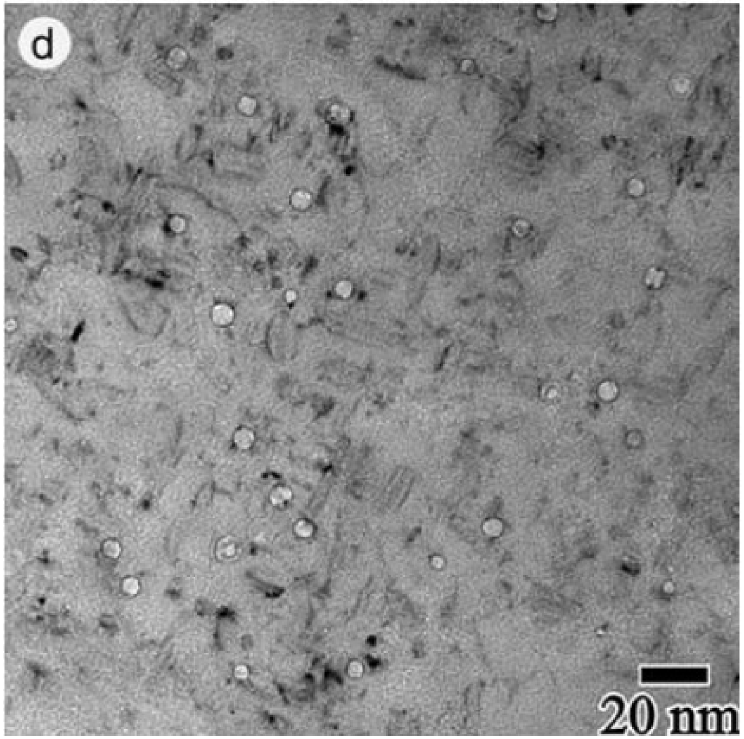
Radiation damage induced microstructural changes in materials

AlMg3 irradiated to 3.6 dpa at ~60℃ at SINQ target



Hamaguchi & Dai, JNM 329-333 (2004) 958.

SS 316 (CW) irradiated to 12.2 dpa at 343℃ at Tihange 1 (PWR)

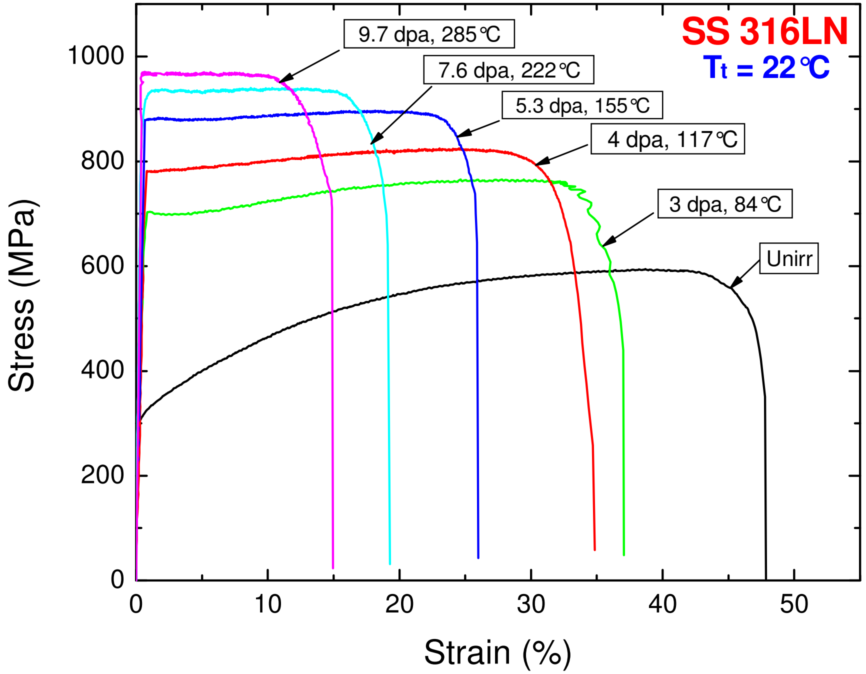


Edwards et al. JNM 317 (2003) 32.

Introduction

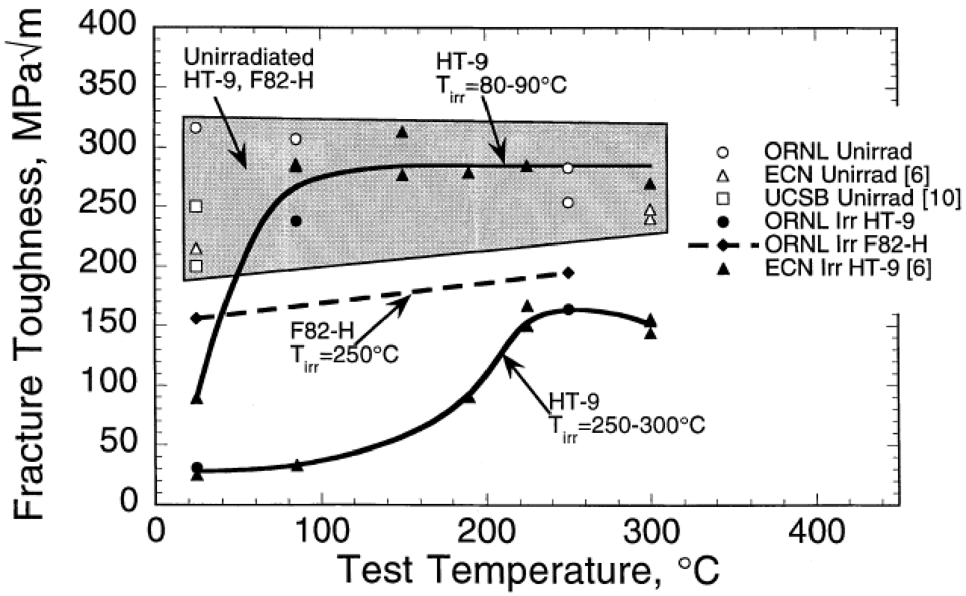
Radiation induced hardening and embrittlement effects in materials

Austenitic stainless steel EC 316 LN irradiated at SINQ target



Dai et al. JNM 377 (2008) 109.

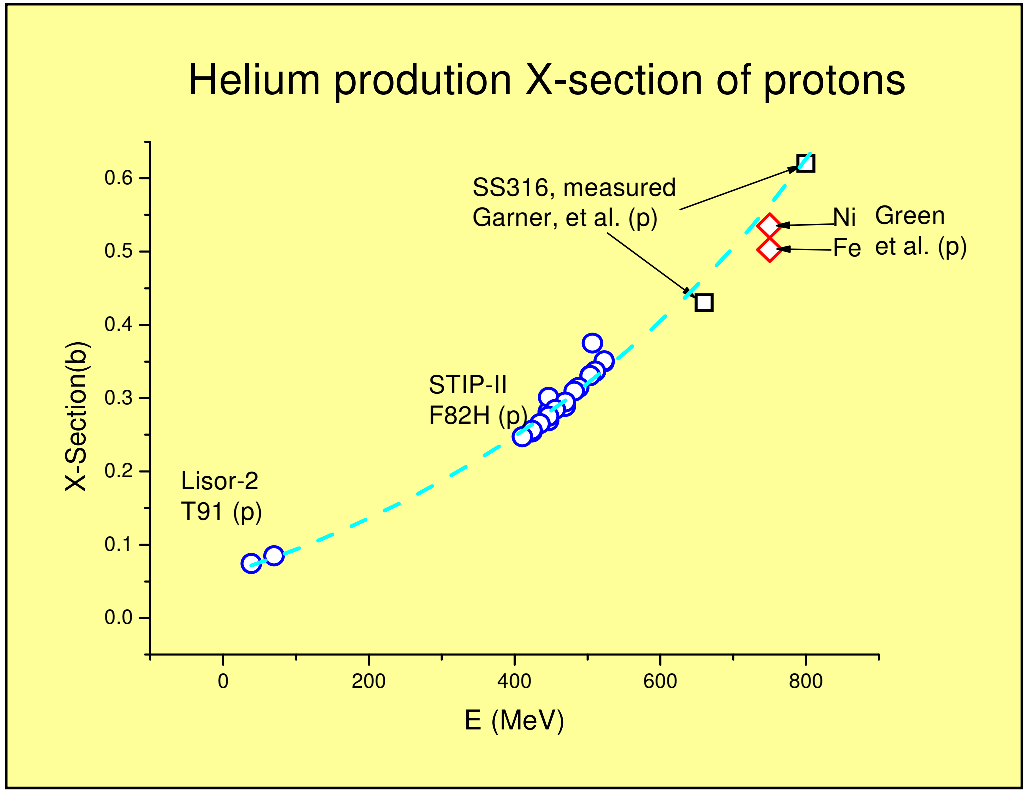
Martensitic steels F82H and HT-9 irradiated to 15-2.5 dpa at HFIR (ORNL)



Rowcliffe et al. JNM 258-263 (1998) 1275.

Introduction

High energy protons induced high He and H production rate in Materials



He-to-dpa ratio

In spallation targets: up-to 100 appm He / dpa

In fusion reactors: 10-15 appm He / dpa

In fission reactors: < 1 appm He / dpa (for most of materials)

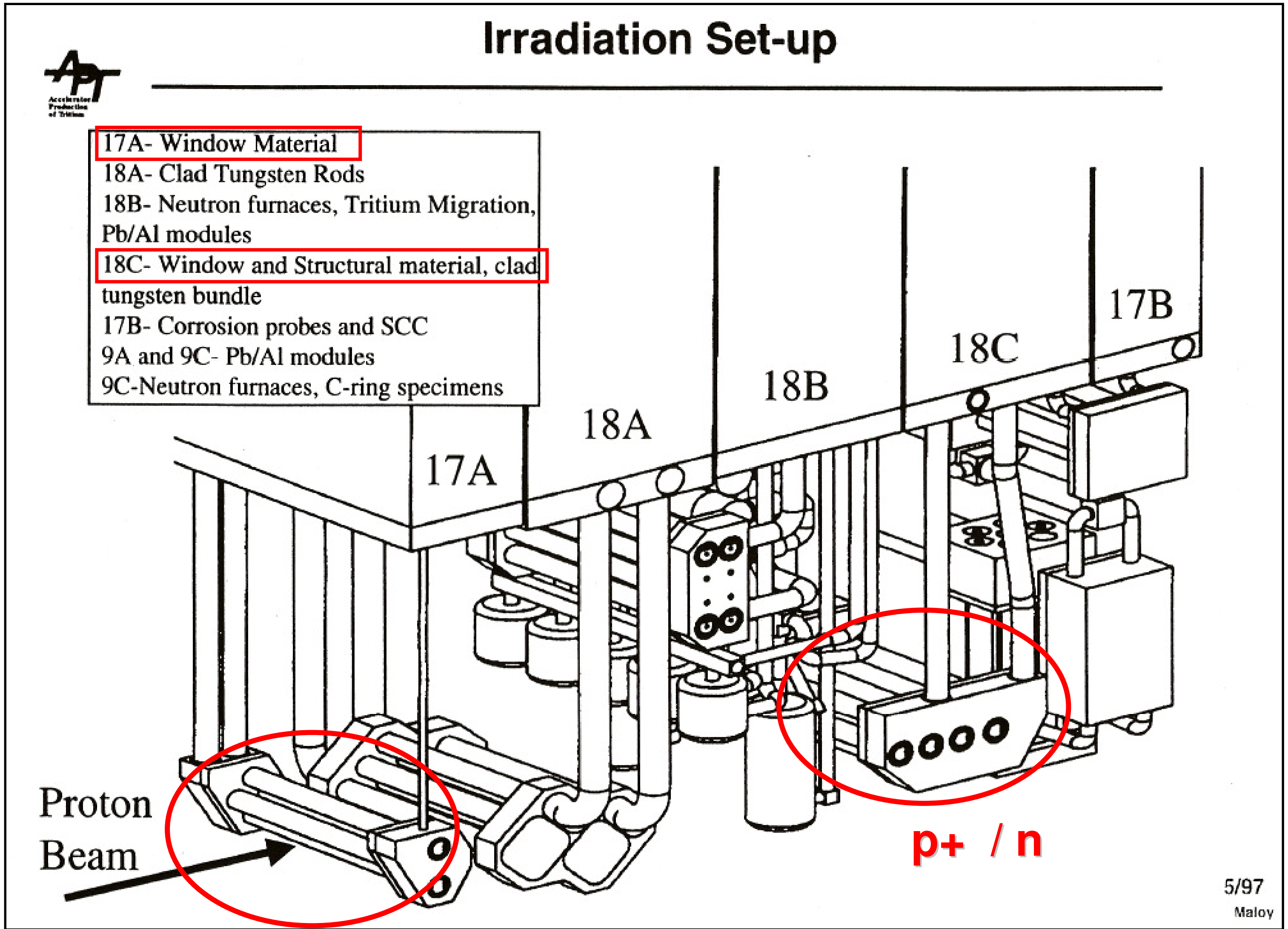
Introduction

❖ For developing high power advanced spallation neutron targets, it is necessary to understand: (1) the synergistic radiation effects of displacement damage, He and H on the hardening and embrittlement, and (2) liquid metal corrosion and embrittlement effects of structural materials.

❖ In order to establish spallation materials database, one irradiation experiment (for APT-Program) was performed at LANSCE during 1996-1997 and five experiments (STIP-I to –V) were done at SINQ during 1998 - 2008.

Irradiation experiments in spallation targets

Irradiation experiment at LANSCE



800 MeV p+ mainly

Maloy & Sommer, IWSMT-2, 1997.

Irradiation experiment at LANSCE

Structural materials irradiated at LANSCE up to ~13 dpa at ≤ 160°C. They are mainly:

Austenitic steels: SS 316L, SS 304L

FM steels: 9Cr-1Mo (mod.), 9Cr-2WTaVNb, F82H

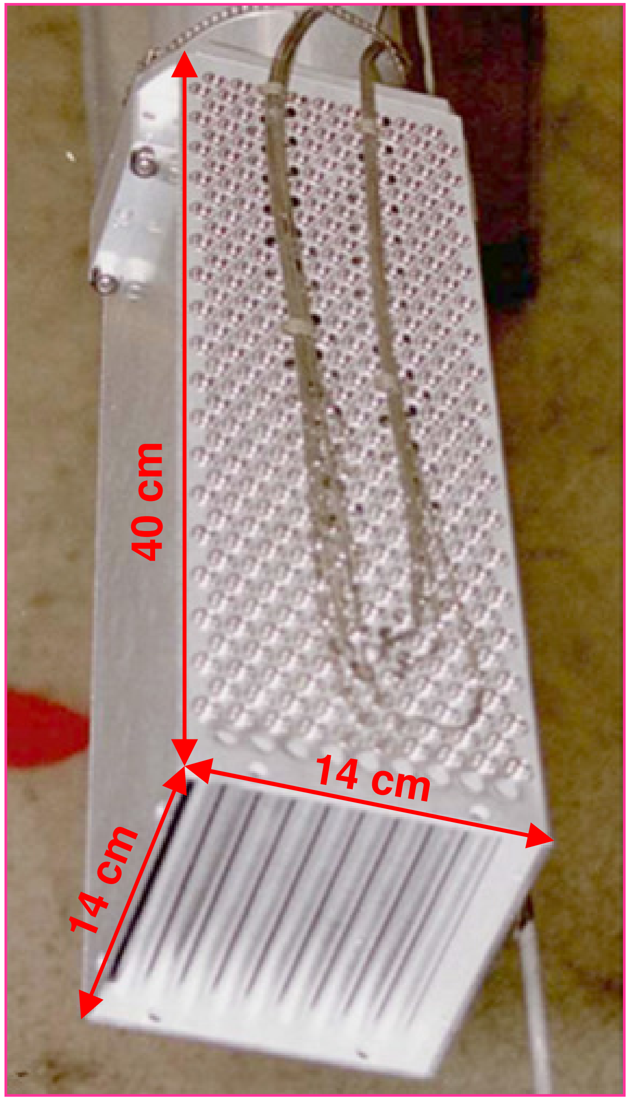
Al-alloys: Al-6061, Al5052-O

Ni-alloy: Inconel 718

Welds: 316L+316L, 316L+Inconel 718, Al alloys+316L,
Al-alloys+Al-alloys

PIE has been conducted.

Irradiation experiments at SINQ (STIP)



~360 rods of Pb with
SS 316L/Zircaloy cladding,
+ 15-20 specimen rods

Max. P-flux:
2.2×10^{14} p/(cm^{2}s).

Max. fast N (>0.1 MeV) - flux:
2.0×10^{14} n/(cm^{2}s).

Irradiation experiments at SINQ (STIP)

Materials	STIP-I	STIP-II	STIP-III	STIP-IV	STIP-V
Austenitic steels	≤ 12 dpa ≤ 400℃	≤ 20 dpa ≤ 400℃	≤ 20 dpa ≤ 400℃	≤ 20 dpa < 400℃(?)	20 dpa 400℃
FM steels (FMS)	≤ 12 dpa ≤ 360℃	≤ 20 dpa ≤ 400℃	≤ 20 dpa ≤ 800℃	≤ 25 dpa < 600℃(?)	20 dpa 400℃
FMS-ODS		≤ 20 dpa < 400℃	≤ 20 dpa ≤ 800℃	≤ 25 dpa < 600℃(?)	20 dpa 600℃
Ni-alloy	≤ 12 dpa ≤ 400℃	≤ 20 dpa ≤ 400℃			
Al-alloy	≤ 3 dpa ≤ 60℃	≤ 6 dpa ≤ 60℃			
Zr-alloy	≤ 22 dpa < 300℃	≤ 35 dpa < 300℃	≤ 35 dpa < 300℃		
Ta		≤ 30 dpa ≤ 350℃		Yes	
Mo, W, alloys	Yes (no results)	Yes (no results)		Yes	Yes
SiCf/SiC, CMC		Yes (to be tested soon)		Yes (to be tested soon)	Yes 800℃

(Yellow) Some samples irradiated in contact with liquid metals, Pb, Pb-Bi or Hg.

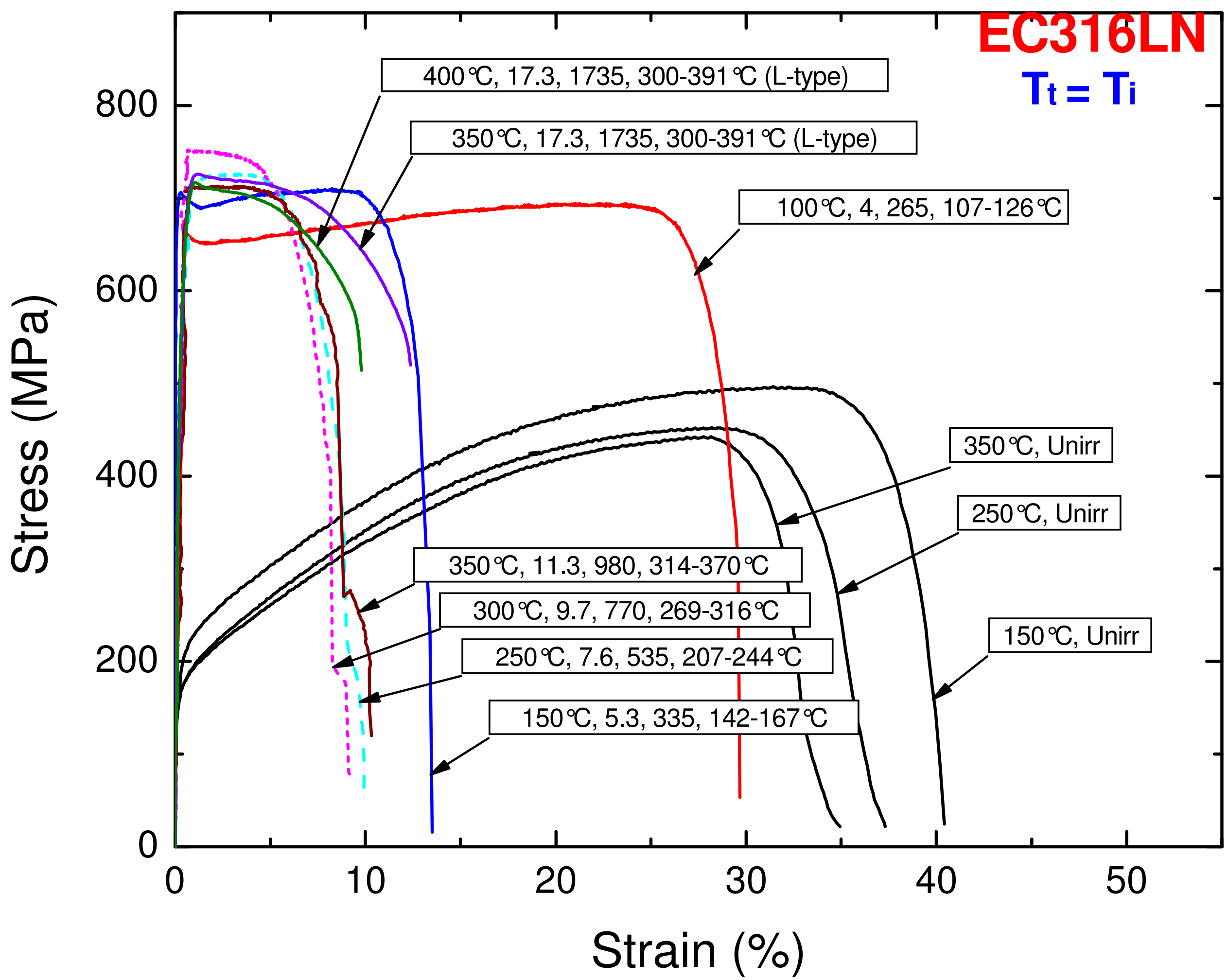
Irradiation experiments at SINQ (STIP)

Materials	STIP-I	STIP-II	STIP-III	STIP-IV	STIP-V
Austenitic steels	≤ 12 dpa ≤ 400°C	≤ 20 dpa ≤ 400°C	≤ 20 dpa ≤ 400°C	≤ 20 dpa < 400°C(?)	20 dpa 400°C
FM steels (FMS)	≤ 12 dpa ≤ 360°C	≤ 20 dpa ≤ 400°C	≤ 20 dpa ≤ 800°C	≤ 25 dpa < 600°C(?)	20 dpa 400°C
FMS-ODS		≤ 20 dpa < 400°C	≤ 20 dpa ≤ 800°C	≤ 25 dpa < 600°C(?)	20 dpa 600°C
Ni-alloy	≤ 12 dpa ≤ 400°C	≤ 20 dpa ≤ 400°C			
Al-alloy	≤ 3 dpa ≤ 60°C	≤ 6 dpa ≤ 60°C			
Zr-alloy	≤ 22 dpa < 300°C	≤ 35 dpa < 300°C	≤ 35 dpa < 300°C		
Ta		≤ 30 dpa ≤ 350°C		Yes	
Mo, W, alloys	Yes (no results)	Yes (no results)		Yes	Yes
SiCf/SiC, CMC		Yes (to be tested soon)		Yes (to be tested soon)	Yes 800°C

PIE has been performed on the specimens under irradiation conditions marked in red colour.

Representative results of austenitic and martensitic steels

Results: Austenitic steels – tensile properties



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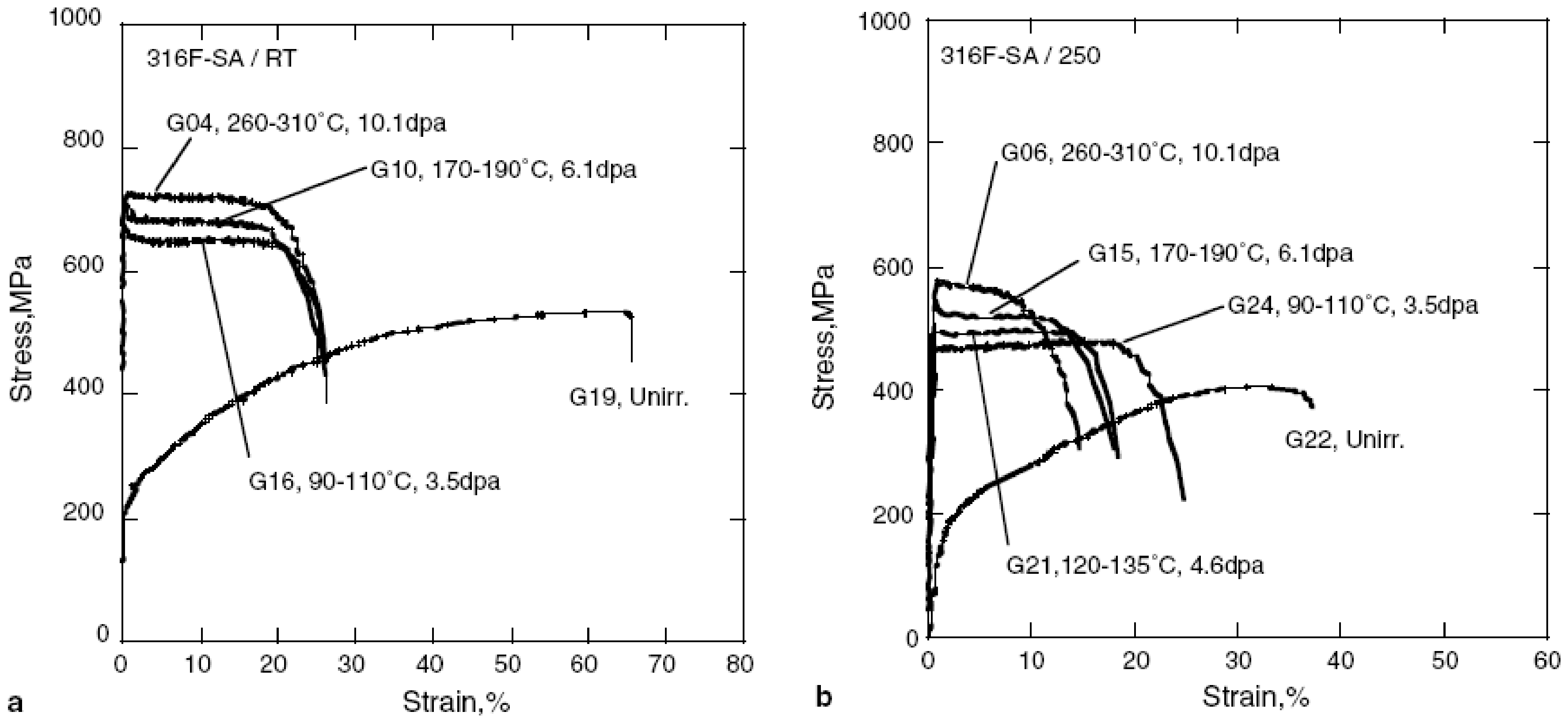
Results: Austenitic steels – tensile properties

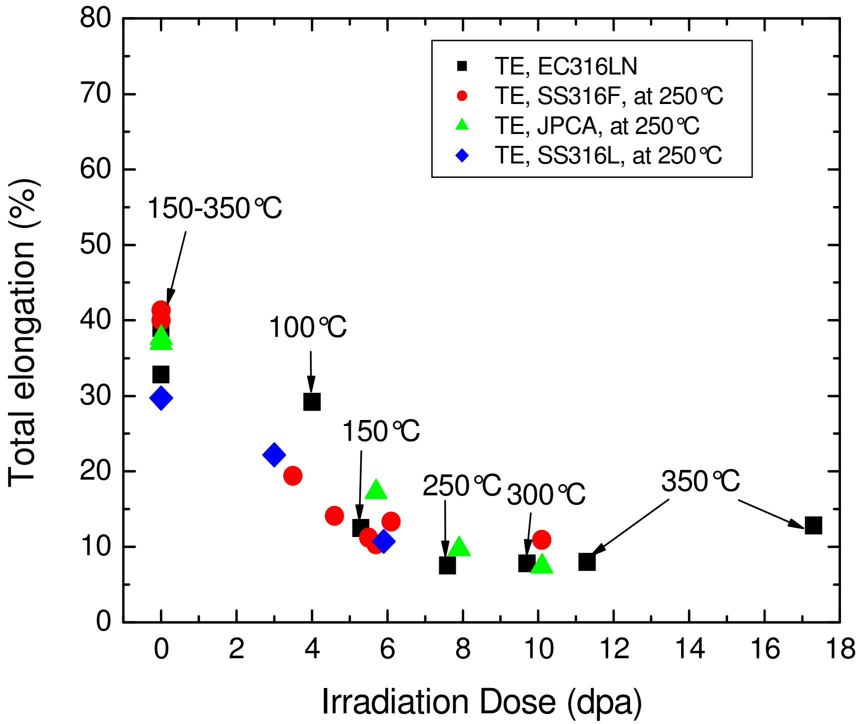
316F-SA irradiated in STIP-I



S. Saito et al. / JNM, 343 (2005) 253

Results: Austenitic steels – tensile properties

STIP



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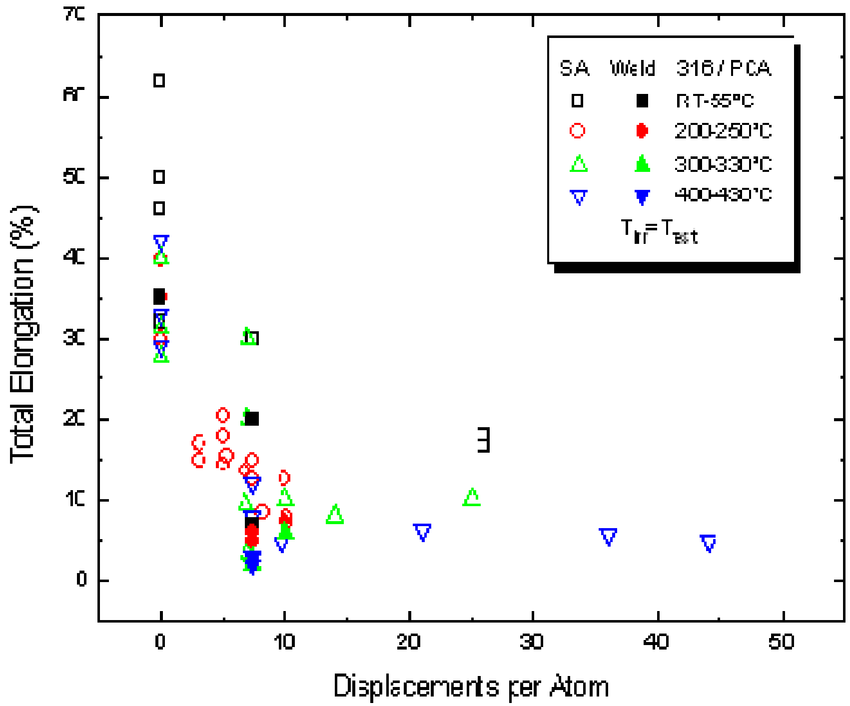
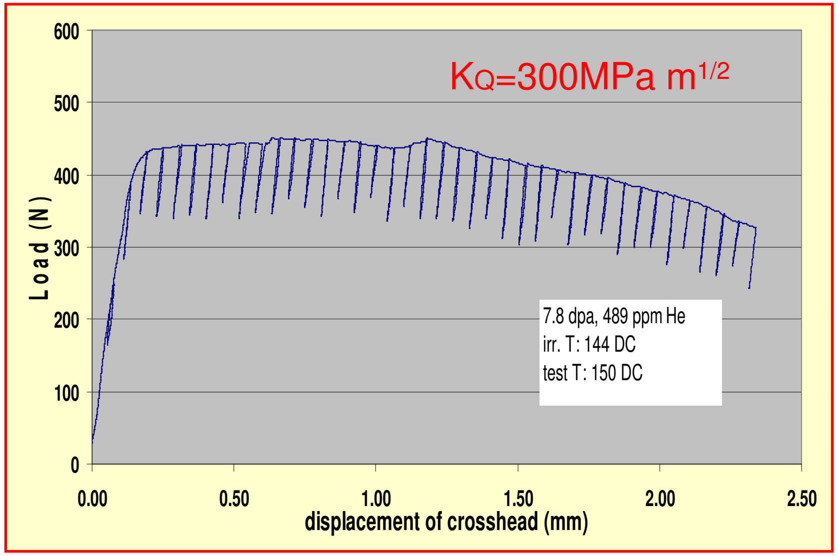
Neutron irradiation

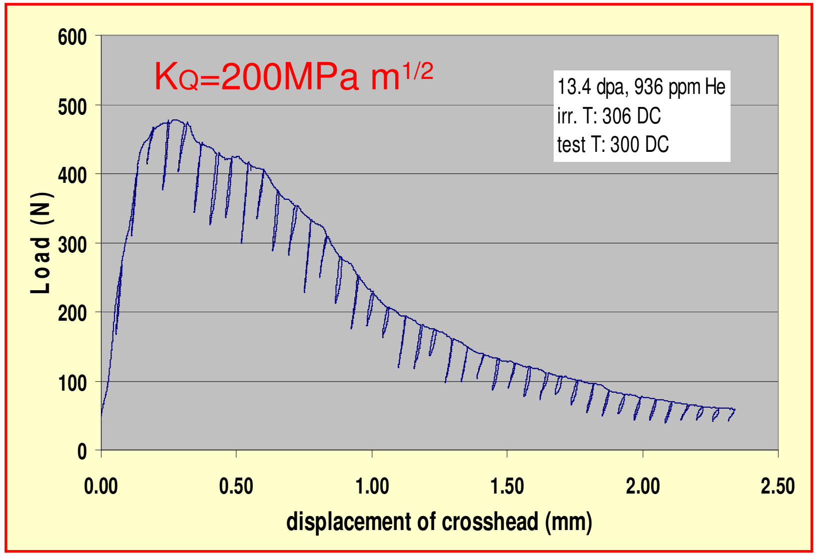


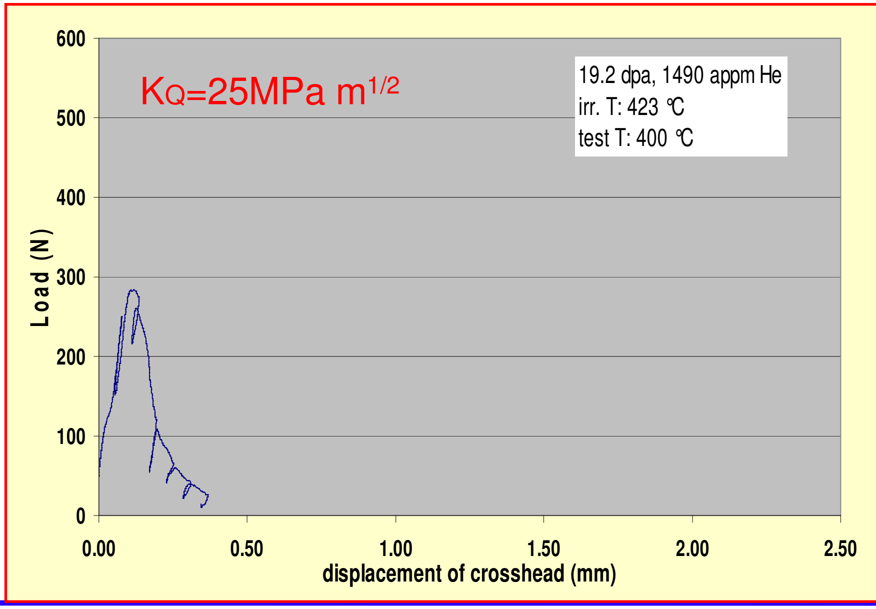
Data from
W.L. Bell, T. Lauritzen and S. Vaidyanathan, in *Proc. Topical Conf. on Ferritic Alloys for Use in Nuclear Technologies*, (AIME, Warrendale, PA, 1984), p. 113.
A. Kohyama, M.L. Grossbeck and G. Piatti, *J. Nucl. Mater.* **191-194** (1992) 37.
G.R. Odette and G.E. Lucas, *J. Nucl. Mater.* **179-181** (1991) 572.
G.R. Odette and G.E. Lucas, *J. Nucl. Mater.* **191-194** (1992) 50.
J.D. Elen and P. Fenici, *J. Nucl. Mater.* **191-194** (1992) 766.
F.W. Wiffen and P.J. Maziasz, *J. Nucl. Mater.* **103&104** (1981)
S. Jitsukawa, P.J Maziasz, T. Ishiyama, L.T. Gibson and A. Hishinuma, *J. Nucl. Mater.* **191-194** (1992) 771.
H. Schroeder and W. Liu, *J. Nucl. Mater.*, **191-194** (1992) 776.
J.E. Pawel, D.J. Alexander, M.L. Grossbeck, A.W. Longest, A.F. Rowcliffe, G.E. Lucas, S. Jitsukawa, A. Hishinuma and K.Shiba, *J. Nucl. Mater.* **212-215** (1994) 442.

As for tensile data, no great difference between STIP and neutron irradiations

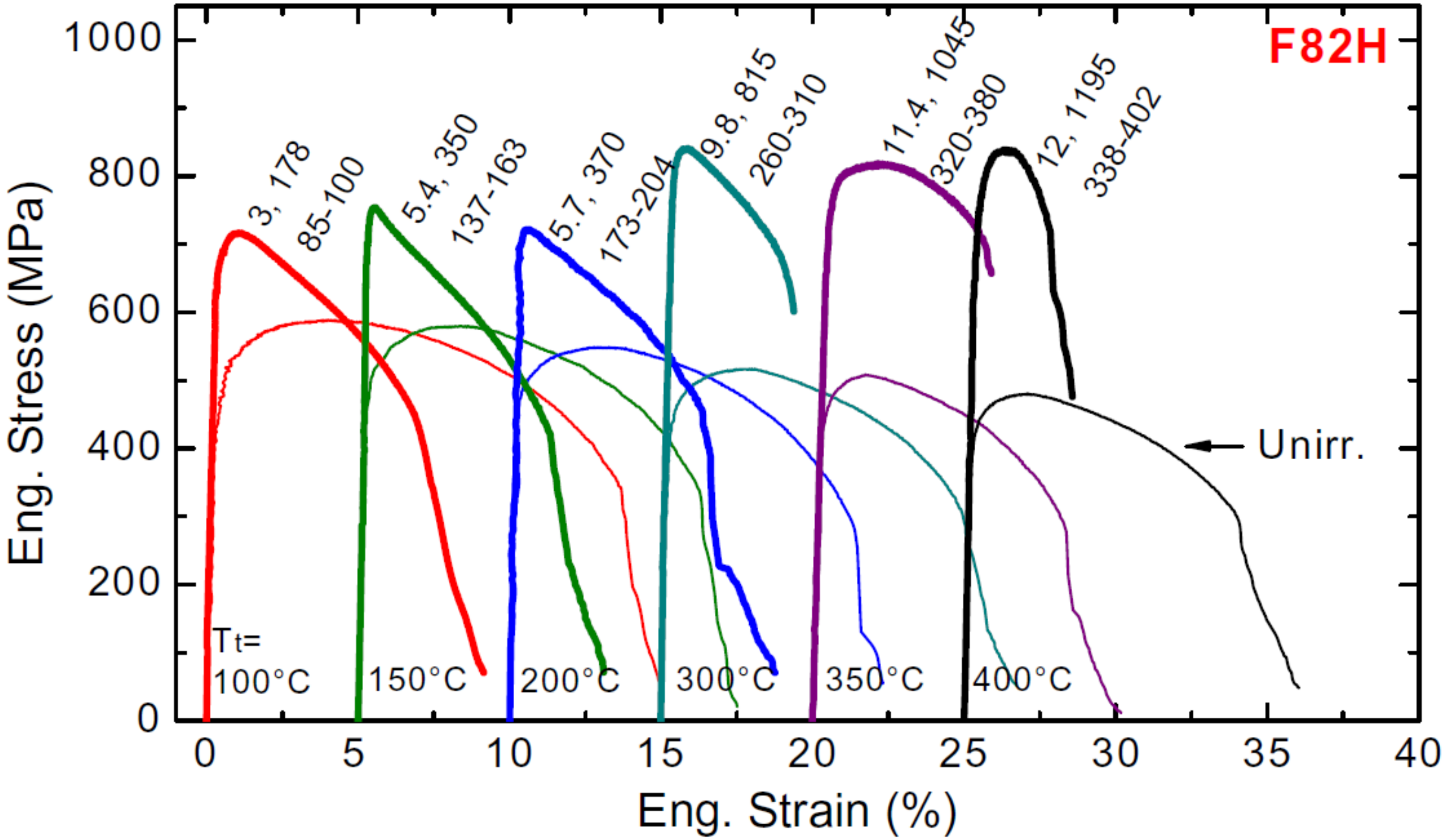
Results: Austenitic steels - fracture toughness





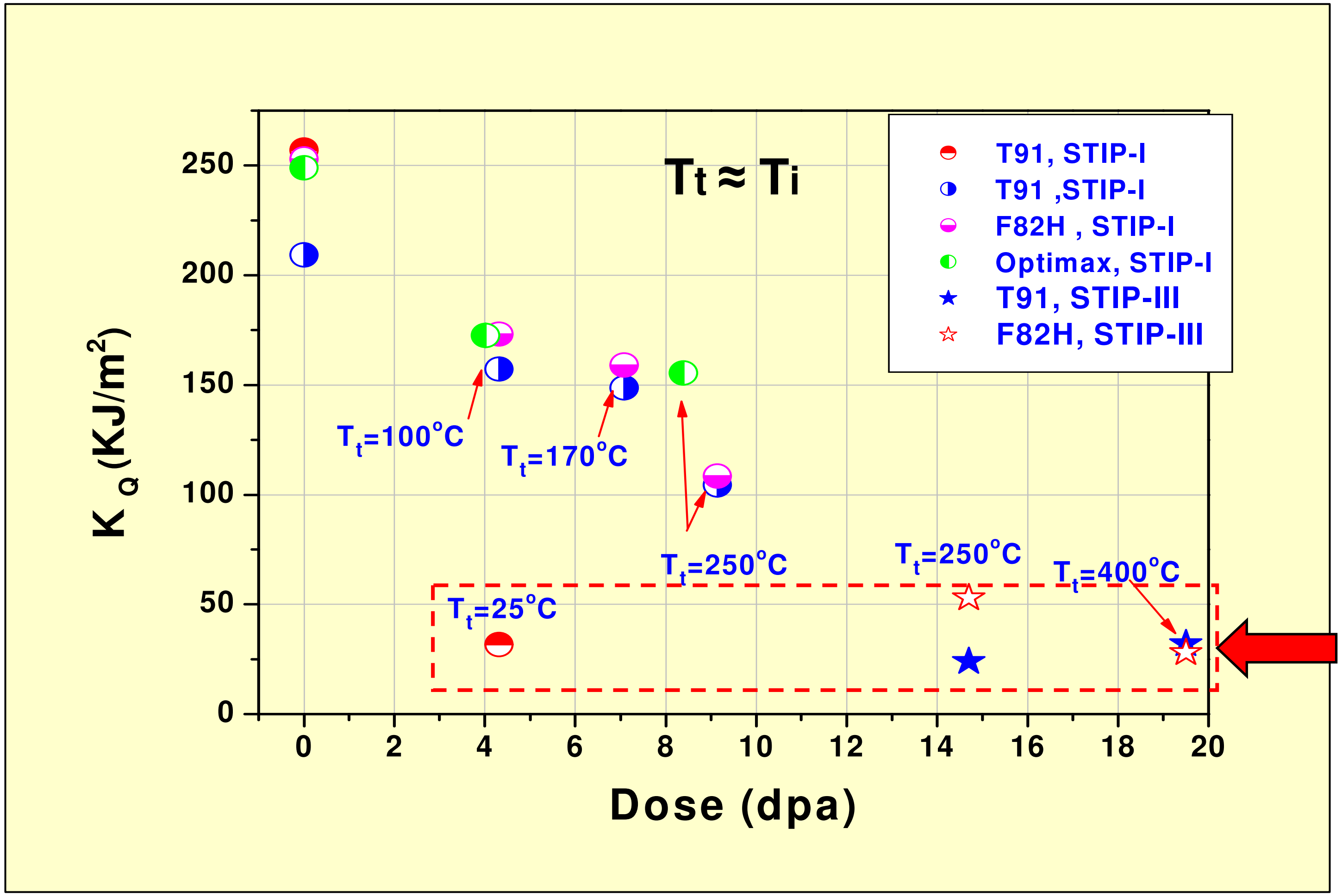


Results: FM steels – tensile properties



Dai, et al. JNM, 377 (2008) 115.

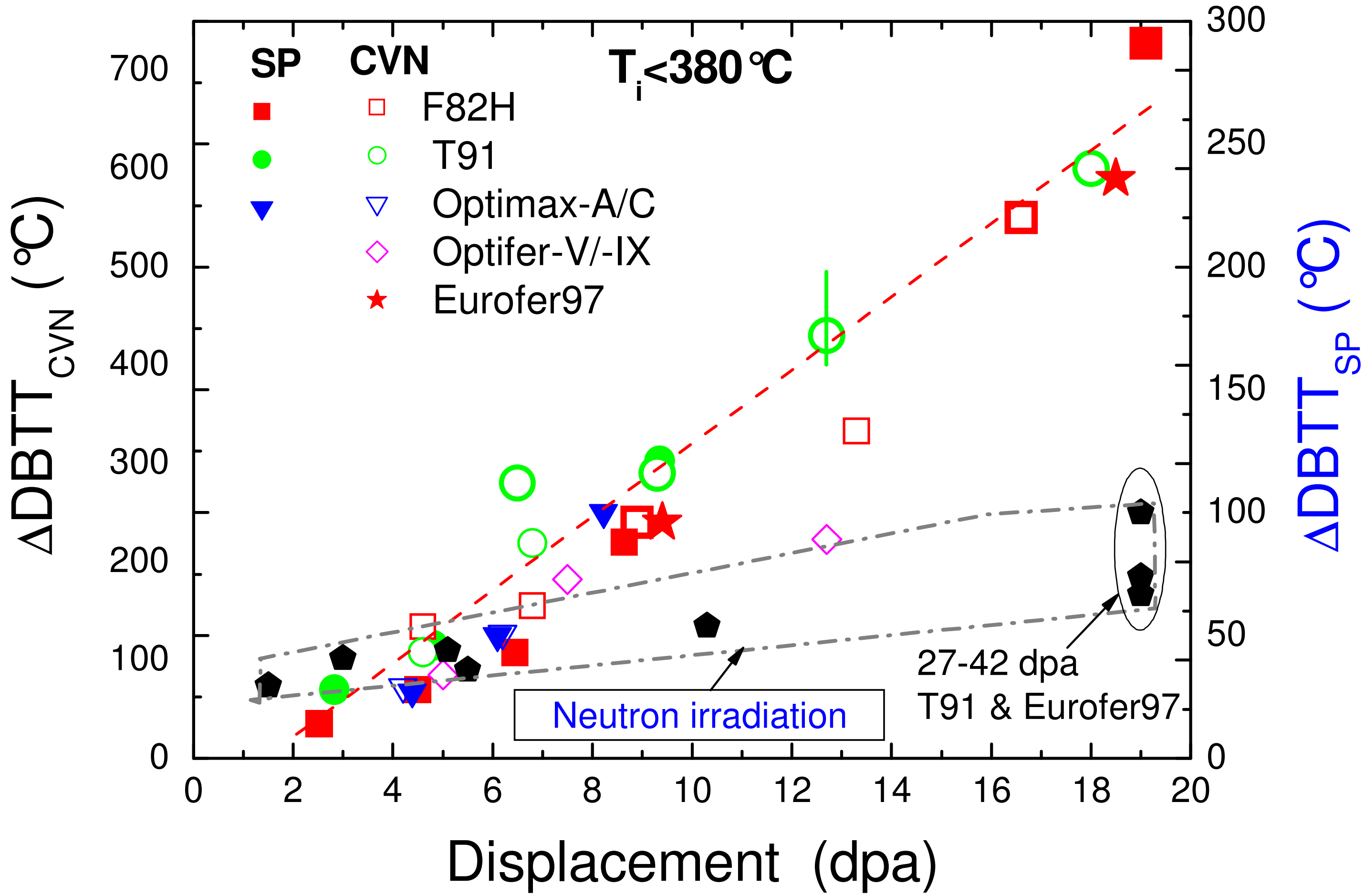
Results: FM steels – fracture toughness



Brittle fracture

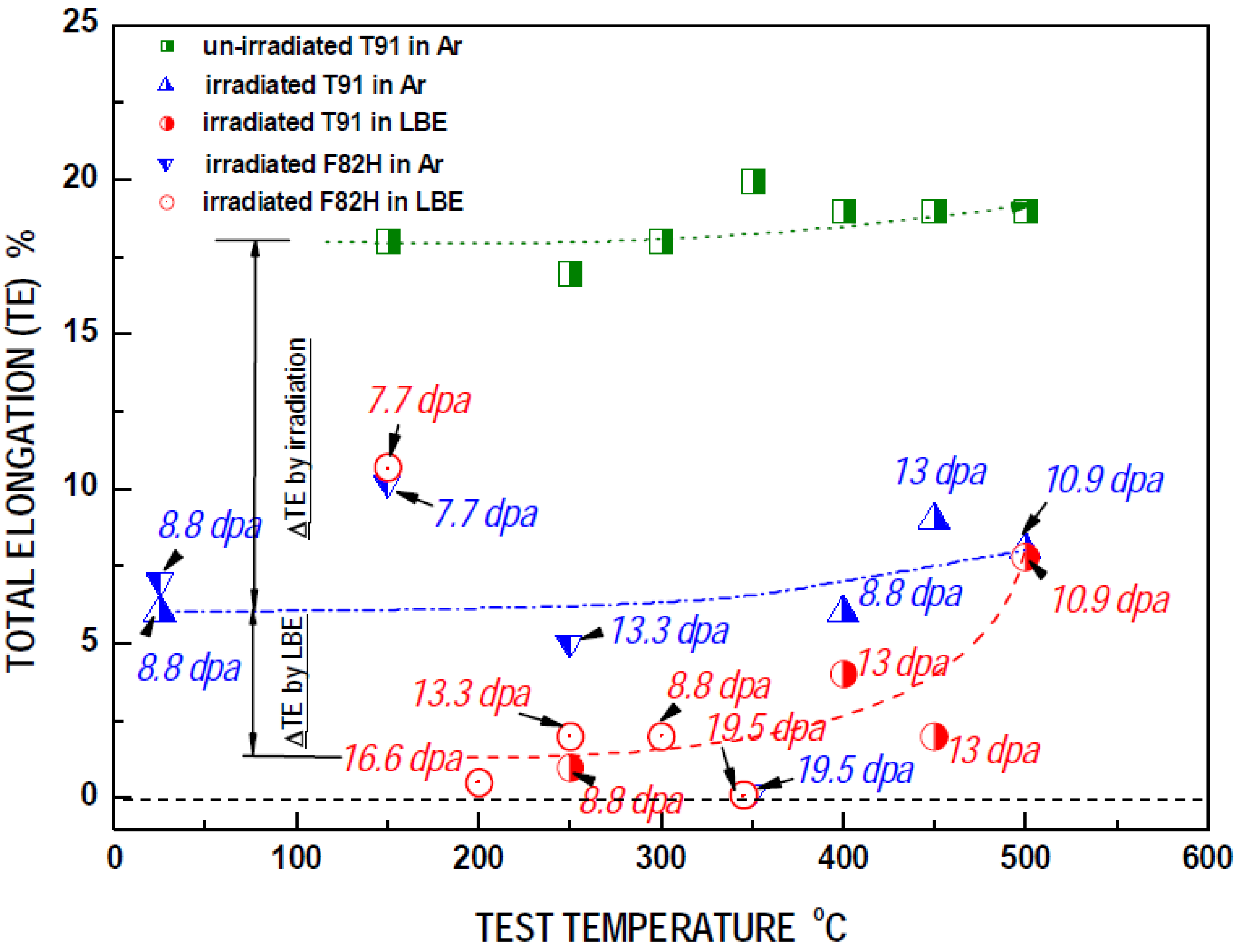
Results: FM steels – DBTT shift

$\Delta DBTT_{SP} = 0.4\ \Delta DBTT_{CVN}$



Neutron irradiation data: (1) Klueh et al, J. Nucl. Mater. 218 (1995) 151; (2) Hu et al. STP 1046 (ASTM, 1990), p.453; (3) Alamo, Euromat2007.

Results: FM steels – LBE embrittlement effects



Long & Dai, to be published in JNM

Summary

❖ **Structural materials such as austenitic and martensitic steels, Ni-, Al-, W-alloys, and ceramics have been irradiated in SINQ targets up to about 20 dpa (in steels) at temperatures up to 800 ℃. PIE has been conducted on a part of specimens of austenitic and martensitic steels and other alloys mostly at lower temperatures < 450℃. The results show a general trend that the degradation of mechanical properties is more pronounced after spallation irradiation as compared that after fission neutron irradiation, particularly for martensitic steels.**

Outlook

- ❖ **Continue the PIE of STIP samples**
- ❖ **Continue irradiation experiments in SINQ targets**
- ❖ **Perform the PIE of the MEGAPIE target**

Outlook: MEGAPIE PIE

Irradiation parameters of the MEGAPIE target

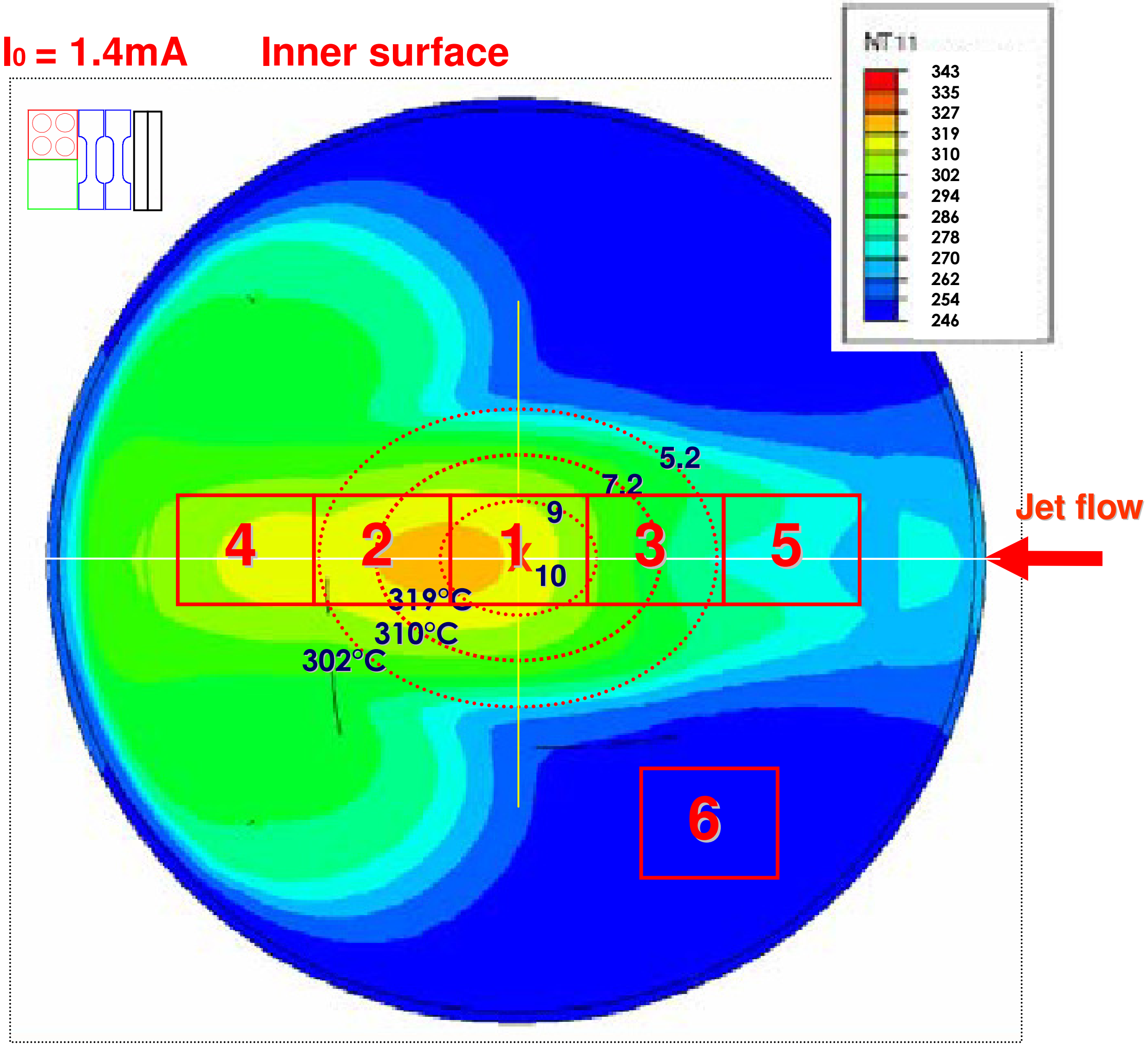
Component	Max. dose (dpa)	Max. Helium concentration (appm)	Irradiation Temp. range (°C)
T91 beam window	6.8	730	250 - 330
SS 316L flow guide tube	2.2	32	250 - 380

Outlook: MEGAPIE PIE

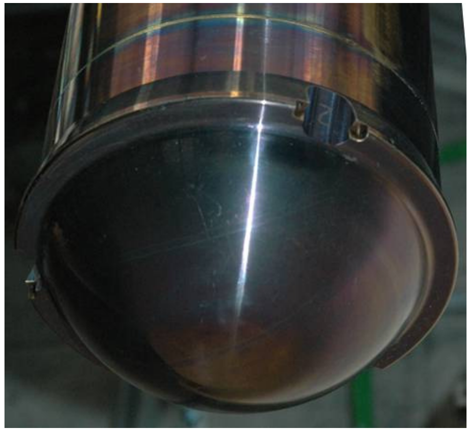
6 conditions (or more):

1: highest dpa & T
2: high T, medium dpa
3: medium dpa & T
4: low dpa, medium T
5: low dpa & T, high flow
6: low dpa, T & flow

I_0 = 1.4mA Inner surface



Outlook: MEGAPIE PIE



	Corro-sion + erosion	Embrittle-ment (irr., He, LBE)	Mechanical change	Microstructural change	Chemical change	Association (number of conditions)
OM + μ-hardness + SEM/EPMA	X	X (μ-hard-ness)				CEA (2 cond) LANL (2 cond) PSI (2 cond) JAEA (2 cond), KAERI
TEM / FEGSTEM		X	X	X	X	CEA (2 cond) FZK (3 cond) PSI (2 cond) JAEA (2 cond), KAERI
H and He analyses		X				PSI (3 cond)
SIMS / XPS	X				X	PSI (SIMS:2cond) SCK (XPS:1cond)
XRD	X				X	CEA (2 cond)
Tensile test		X	X			CEA (2 cond) LANL (2 cond) PSI/ENEA(3cond)* KAERI
Bending test		X	X			LANL (3cond) PSI (3 cond)*
Small punch test **		X	X			CEA (2 cond) PSI (2 cond) CNRS (3 cond)*

* Tests to be done in both Ar (or Air) and LBE environments.
** CNRS will use 8.9 mm diameter discs and the others will use 3 mm diameter discs.

Thank You!