The Abdus Salam
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Principles of Design of Radiation Resistant Materials for Fast Reactor Fuel Assembly: SCOPE

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Principles of Design of Radiation Resistant Materials for Fast Reactor Fuel Assembly: SCOPE

INTRODUCTION TO STEELS;

STRENGTHENIG MECHANISMS IN AUSTENITIC STEELS;

20 % CW 316 AUSTENITIC STAINLESS STEELS TO D9: DESING PRINCIPLES;

AUSTENITICS TO FERRITIC STEELS &

OXIDE DISPERSION STRENGTHENED STEELS.

RECAP:

Reactor circuits: core, out-of-core & balance of plant;

Severe service conditions for core component materials;

Major problems: void swelling, irradiation growth, hardening, crrep and embrittlement;

Main cause is point defects, defect clusters & their interaction with matrix defects;

Void swelling: condensation of excess vacancies into voids, CW, dose, dose rate, temperature type of sinks influence the growth rate

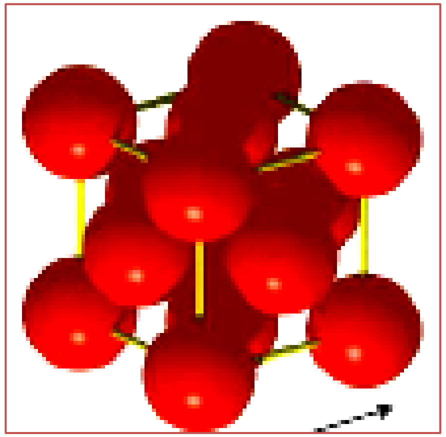
Irrad. Hard.: increase in strength due to defect clusters

Irrad. Creep : diametral strain increase due to SIPA, SIPN & void swelling

Irrad. Embrittlement : DBTT reduces with reduction in upper shelf energy, due to increase in yield strength due to irradiation .

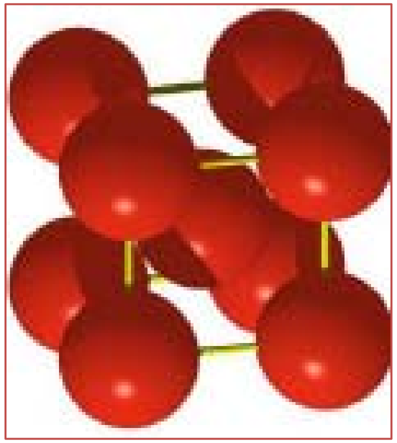
PHASES IN STEELS

PHASE TRANSFORMATIONS IN Fe ALLOYS	
Temperature	
1550 °C	Liquid
1500 °C	δ + Liquid
1400 °C	δ
1200 °C	γ + δ
920°C	γ
800°C	α+ γ
RT	α

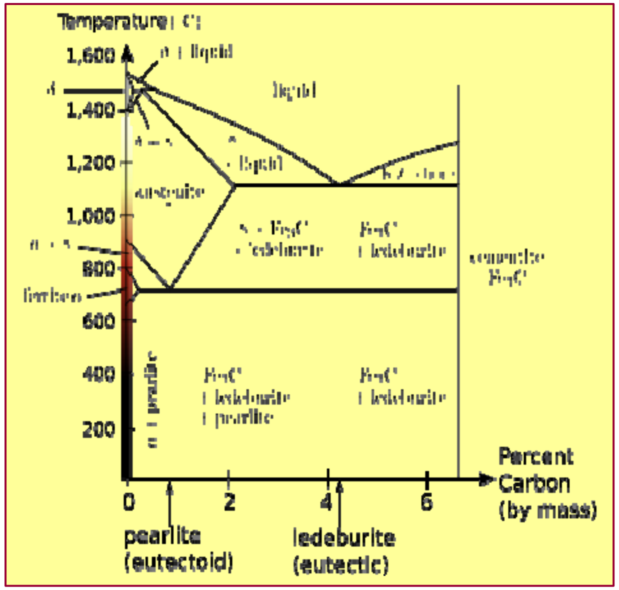


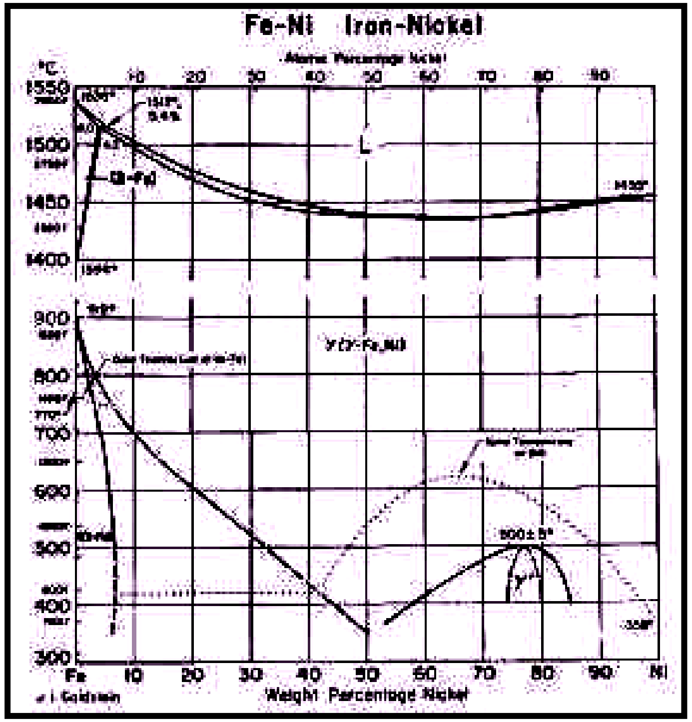
AUSTENITE -γ

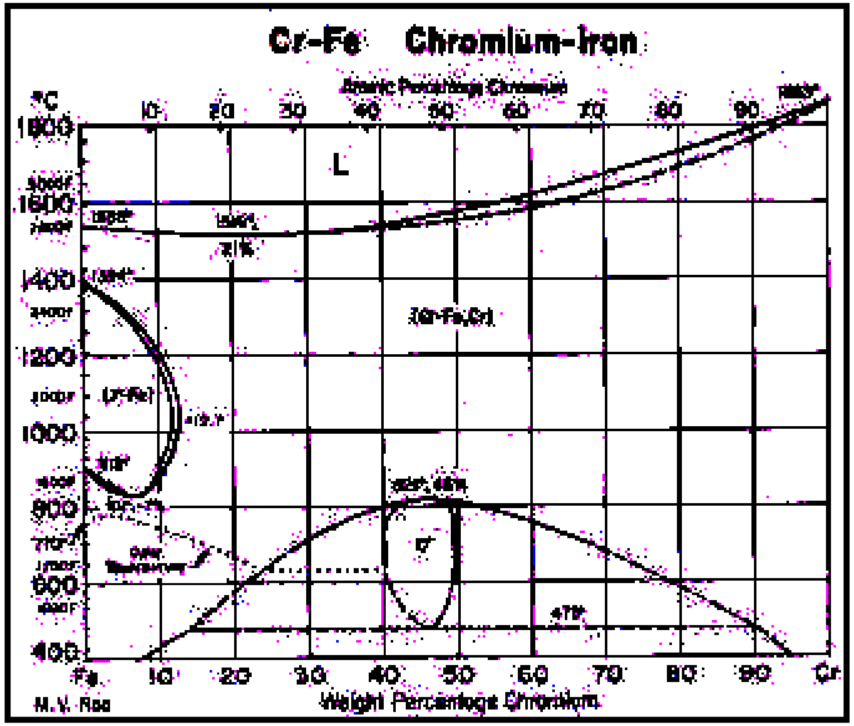
FERRITE - α



Relevant phase diagrams







TARGETS FOR FAST REACTOR MATERIALS SCIENTISTS -

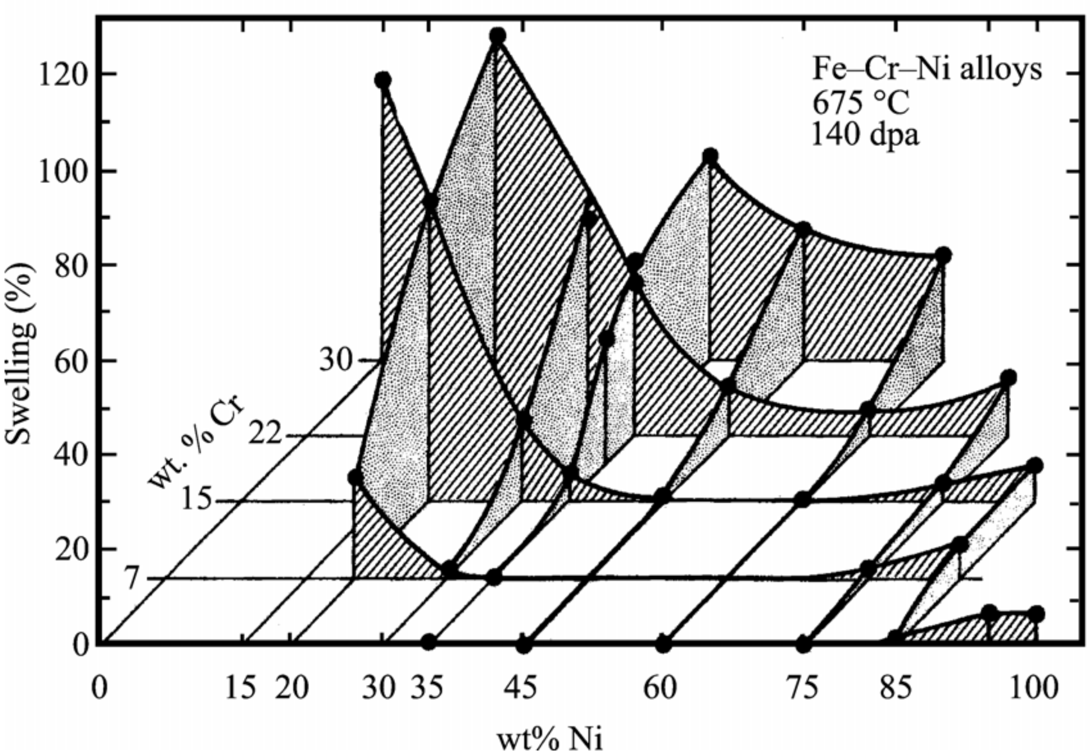
HIGH BURN-UP;

HIGH TEMPERATURE CAPABILITY;

LONG LIFE.

Ni -→ BENEFICIAL FOR
SWELLING RESISTANCE;

Cr -→ BAD BEYOND 15 %.



Ni -- ■ --- 0.26 eV

Cr -- ■ --- 0.06 eV

Can you explain why binding energy with vacancies influences void swelling ?

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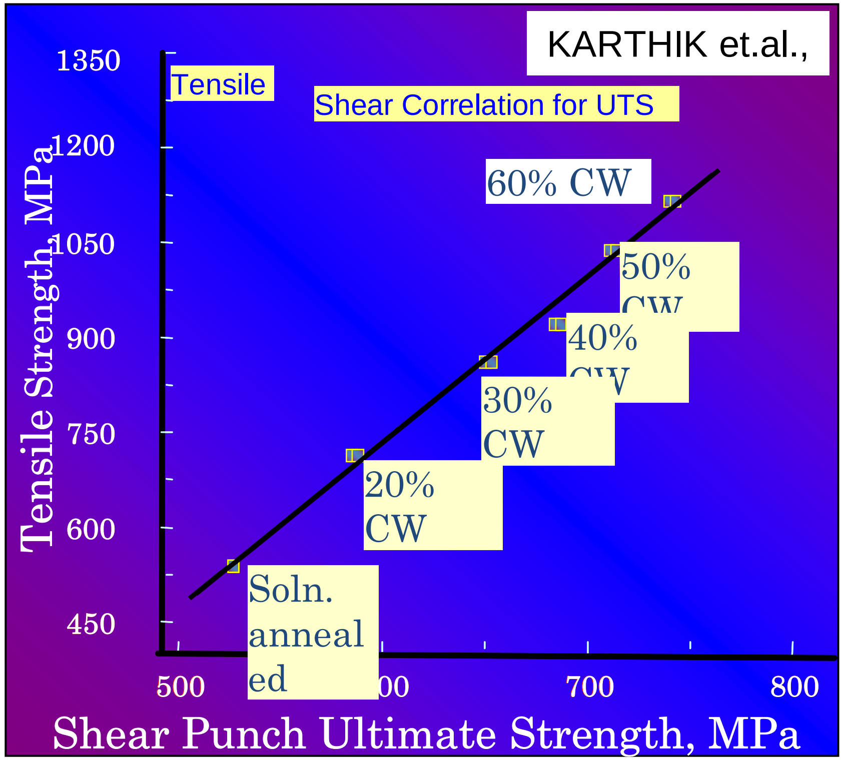
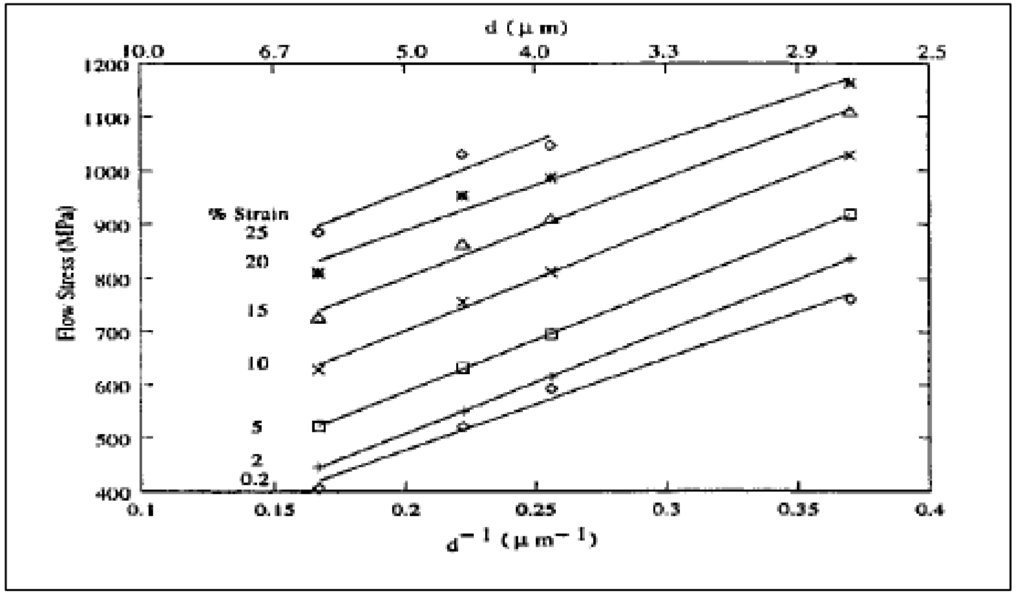
IMPROVING SWELLING RESISTANCE & MECHANICAL PROPERTIES



STRENGTHENING BY CARBON & MOLYBDENUM ADDITION



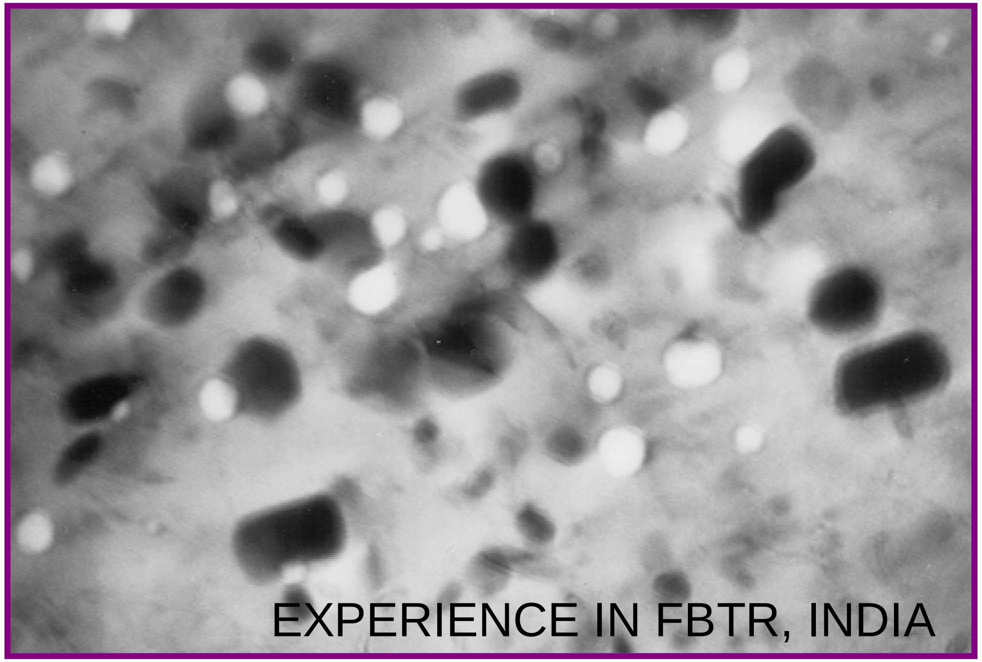
20 % COLD WORKED 316 STAINLESS STEEL ---→ FOR FAST REACTOR CORE

WAS 20 % cw SS OK?

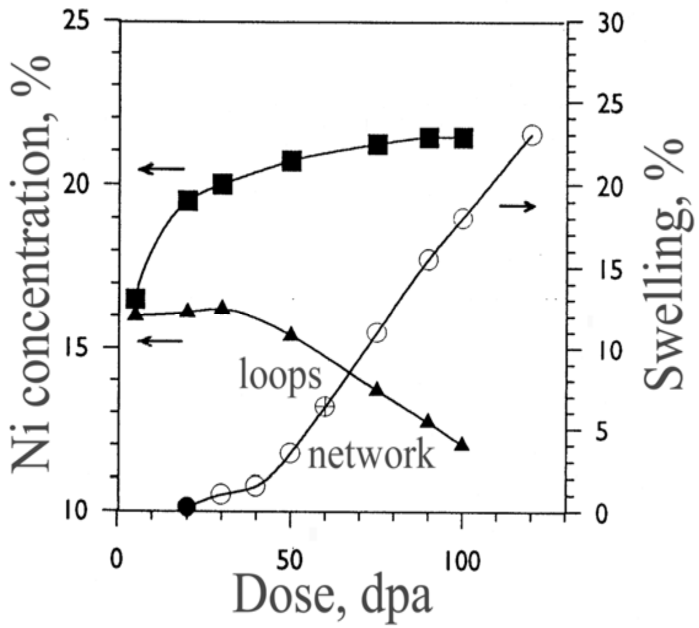
NO !!! ACHIEVABLE BURN-UP IN FRENCH REACTOR WAS ONLY ~ 40 dpa !!!

IN-REACTOR EXPERIENCE NOT SATISFACTORY :

Ni3Si DUE TO RIS & VOIDS AROUND G-PHASE ; γ' PHASE – SOLID SOLUTION DECAY



EXPERIENCE IN FBTR, INDIA



WHAT NEXT ?

ADD Ti TO HAVE TWO ADVANTAGES: BIND THE VACANCIES (0.3 eV), FORM TiC- COHERENT PRECIPITATES

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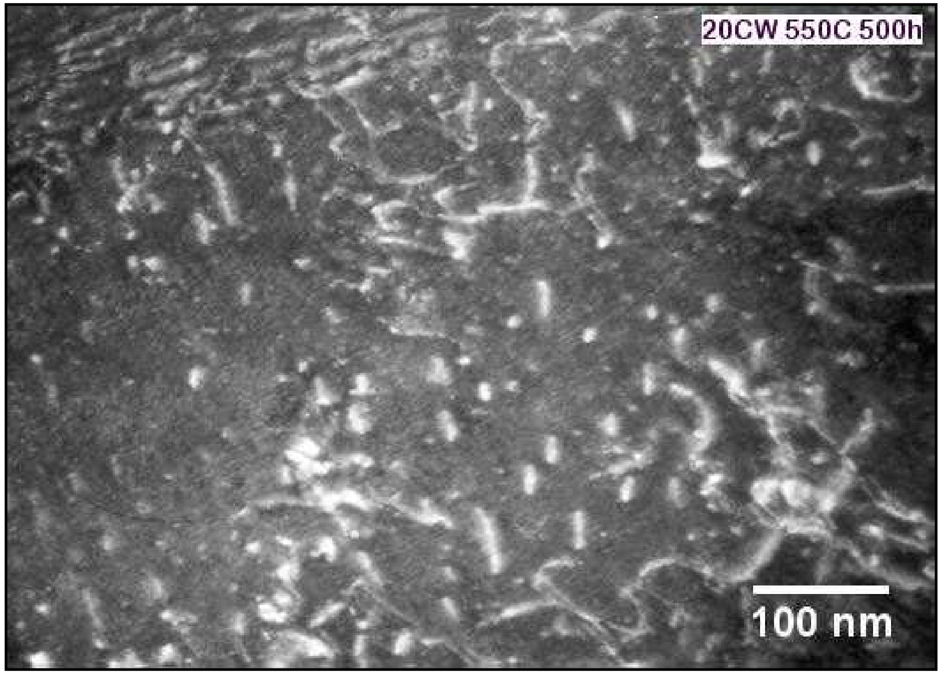
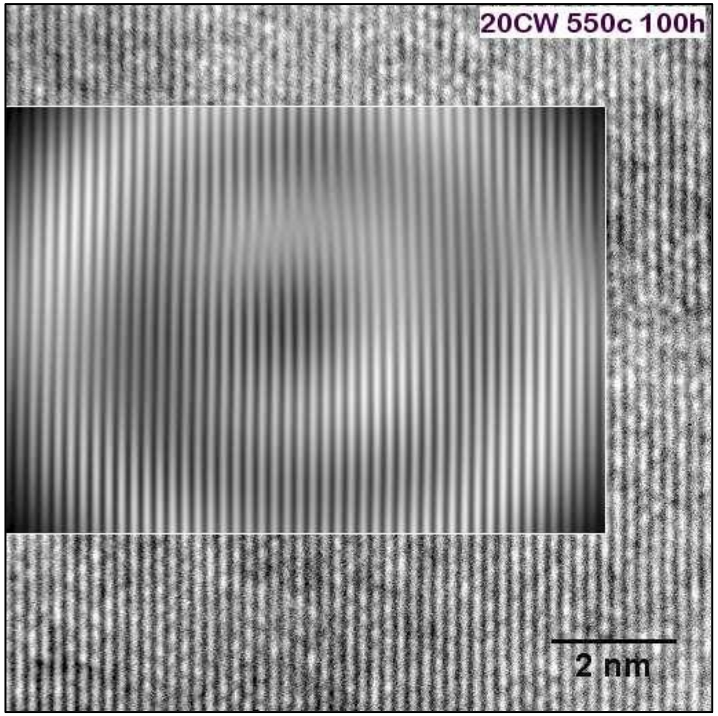
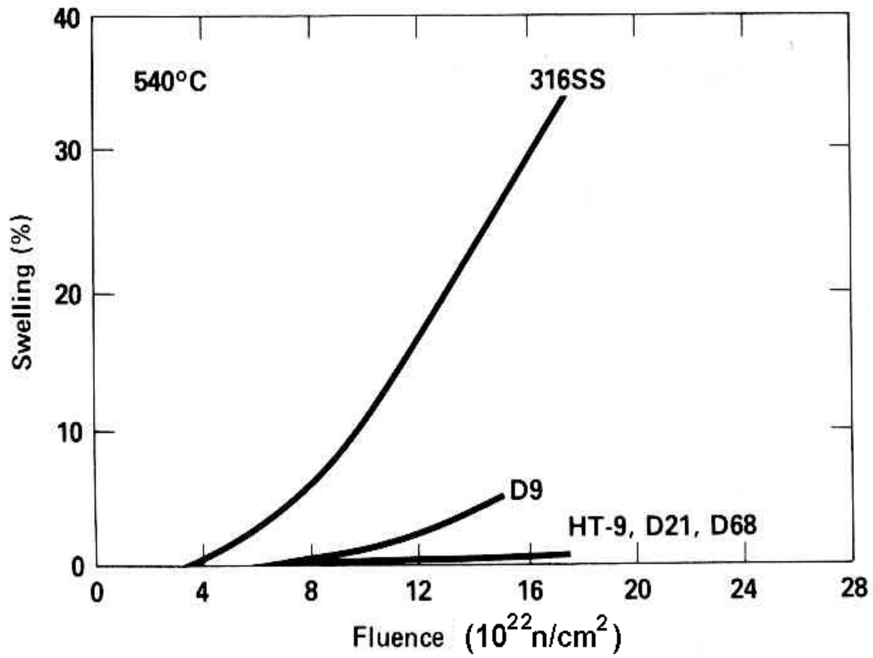
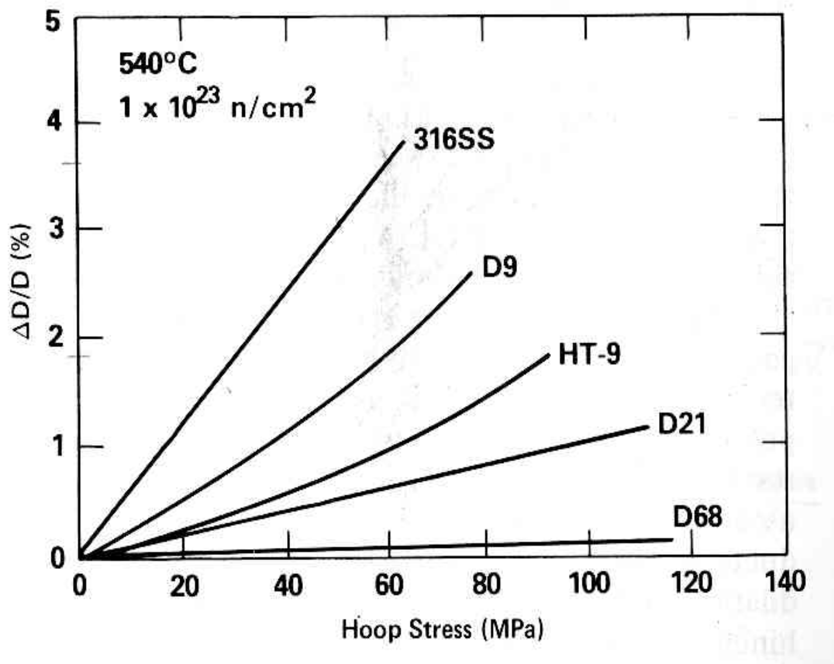
20 % cw 316 STAINLESS STEEL --→ 15 % Ni-15 %Cr-Ti-SS(D9)





Void swelling & irradiation creep

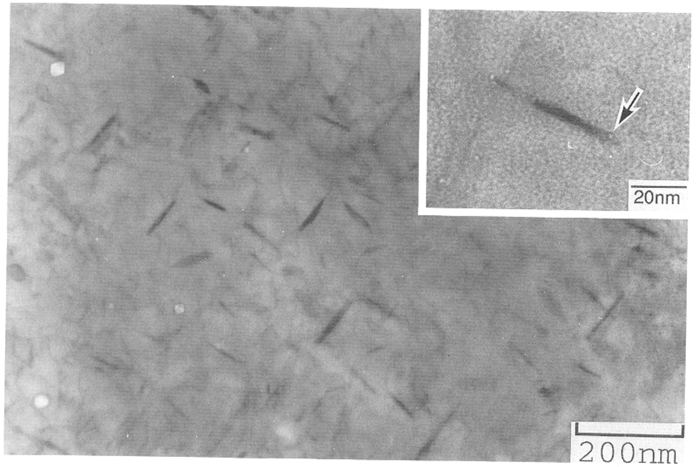


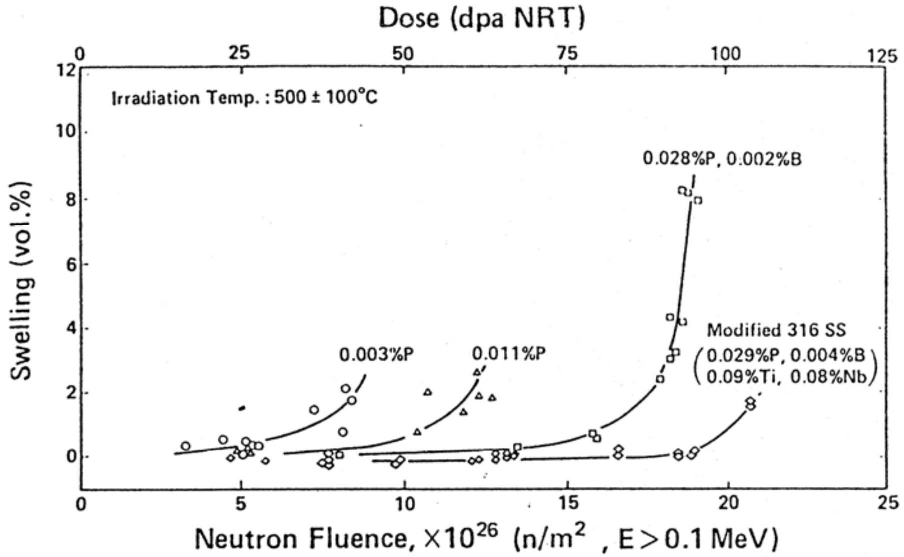


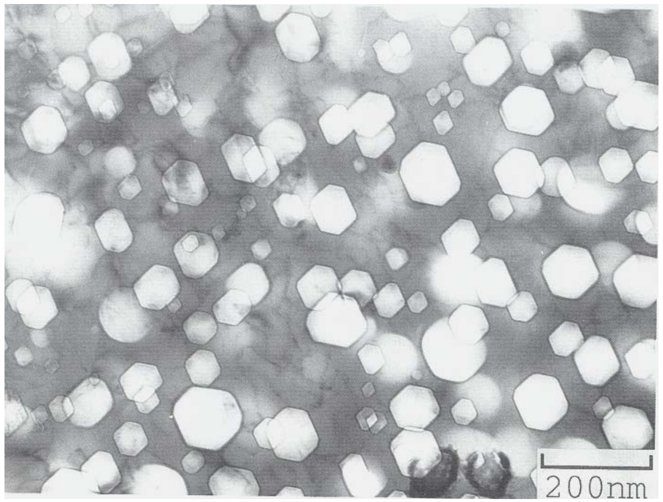
MAXIMUM BURN-UP RAISED TO ~ 80 dpa,
AFTER OPTIMISING Ti/C RATIO

CAN THE BURN-UP LIMIT BE INCREASED FURTHER ????

100-120 dpa with D9i







Role of alloying elements-every element in steels composition

B plays positive role;

increasES radiation resistance IF IT IS IN SS of ASS;

Boron reduces diffusion mobility of carbon and nitrogen ;

restricts formation of carbides and intermetallics.

concentration of Ni, Mo, Si, C, Nb in γ-solid solution is same as original.

Silicon has positive role;

diffusion mobility on some orders higher in comparison with main components of austenitic steels.

silicon, reduces vacancies super saturation and, accordingly, depress rate of their nucleation.

Role of alloying elements-every element in steels composition

Ti – positive role;

Ti-Vacancy BE 0.3 eV; Cv are absorbed by Ti;

Supersaturation of vacancies reduced and swelling reduced;

Ti successfully suppress swelling only together with silicon and phosphorus or with both of them.

Phosphorous – positive role in small amounts;

Diffusion of P-V complex very high with high BE;

phosphorus affects the microstructure via phosphorus-defect interaction at

lower temperatures and via phosphides formation at higher temperatures.

Precipitates classification

- Precipitates EVOLVE IN AUSTENITE DURING LONG TERM SERVICE.
- TWO MAJOR CLASSIFICATION :
- MC (mainly TiC, NbC, VC) Fe_2P or Ni_3Ti (in a few cases) SUPPRESS SWELLING (enhance point defect recombination at particles-matrix interface) - DESIRABLE
- M_6C and G-phases : DRASTICALLY INCREASE SWELLING - solution decay (remove Ni & Si from austenite) - UNDESIRABLE

DESIGN PRINCIPLES OF D9i

ADD ELEMENTS WITH HIGH BINDING ENERGY WITH VACANCIES, LIKE P, Si

------→ ADJUSTMENT OF MINOR ELEMENTS ;

PLAY WITH COPMBINATION OF UNDERSIZED AND OVERSIZED ATOMS TO CAPTURE BOTH VACANCIES & INTERSTITIALS;

COMBINE THE COHERENT PRECIPITATES WITH + AND – MISFIT VOLUME TO ATTRACT OPPOSITE TYPE OF POINT DEFECTS.

SOMEHOW REDUCE OVERALL POINT DEFECT CONCENTRATION
&
VACANCY SUPERSATURATION, IN PARTICULAR.

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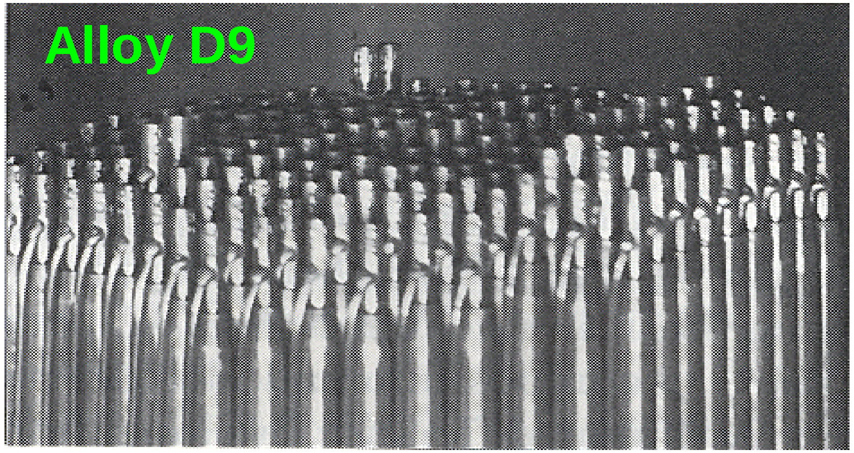
CAN BURN-UP OF FUEL BE INCREASED FURTHER ?

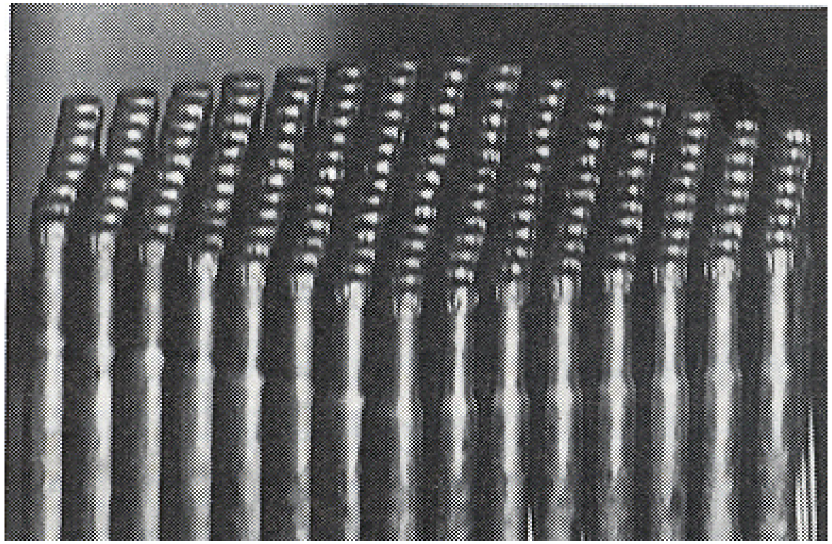
200 – 250 dpa ???

is there a max. limit for burn-up ?

What limits it?

SERENDIPITY IN DEV. OF SWELLING RESISTANT MATERIALS



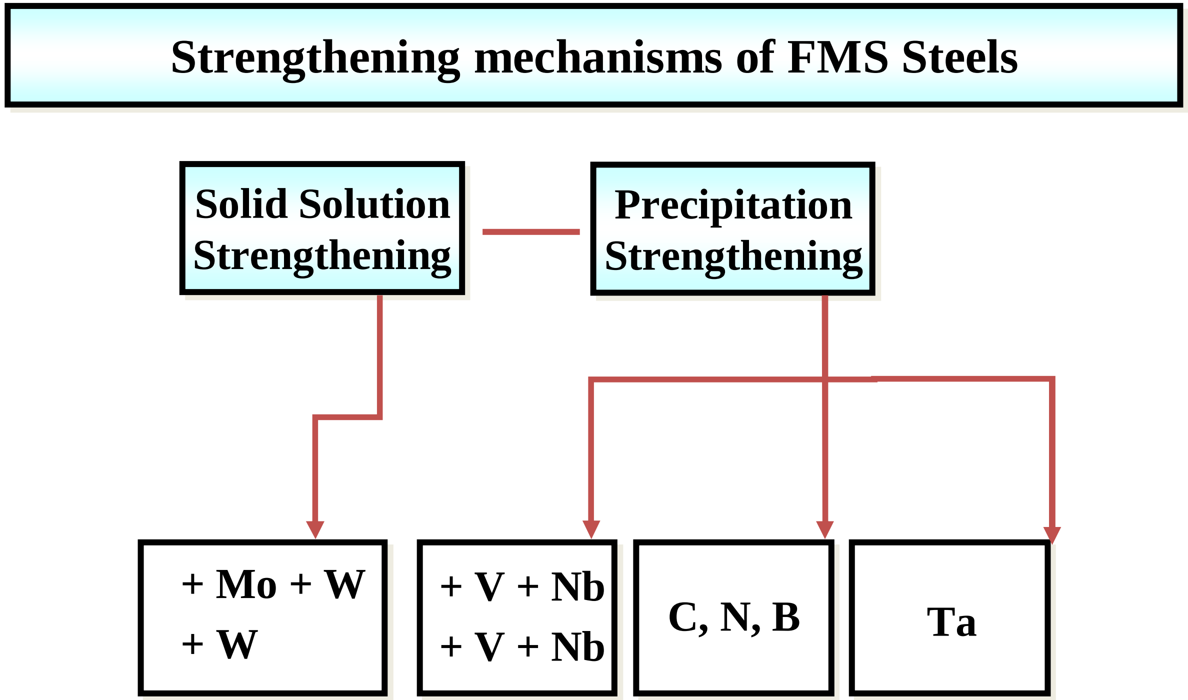


- ✓**E_m^V=0.5eV (< γ)**
- ✓**B.E.-C/- 0.8eV;(>> γ)**
- ✓**Strong ϒ-C Attraction;**
- ✓ **lowRelaxation volume reduced bias**

Burn-up upto 180 – 200 dpa

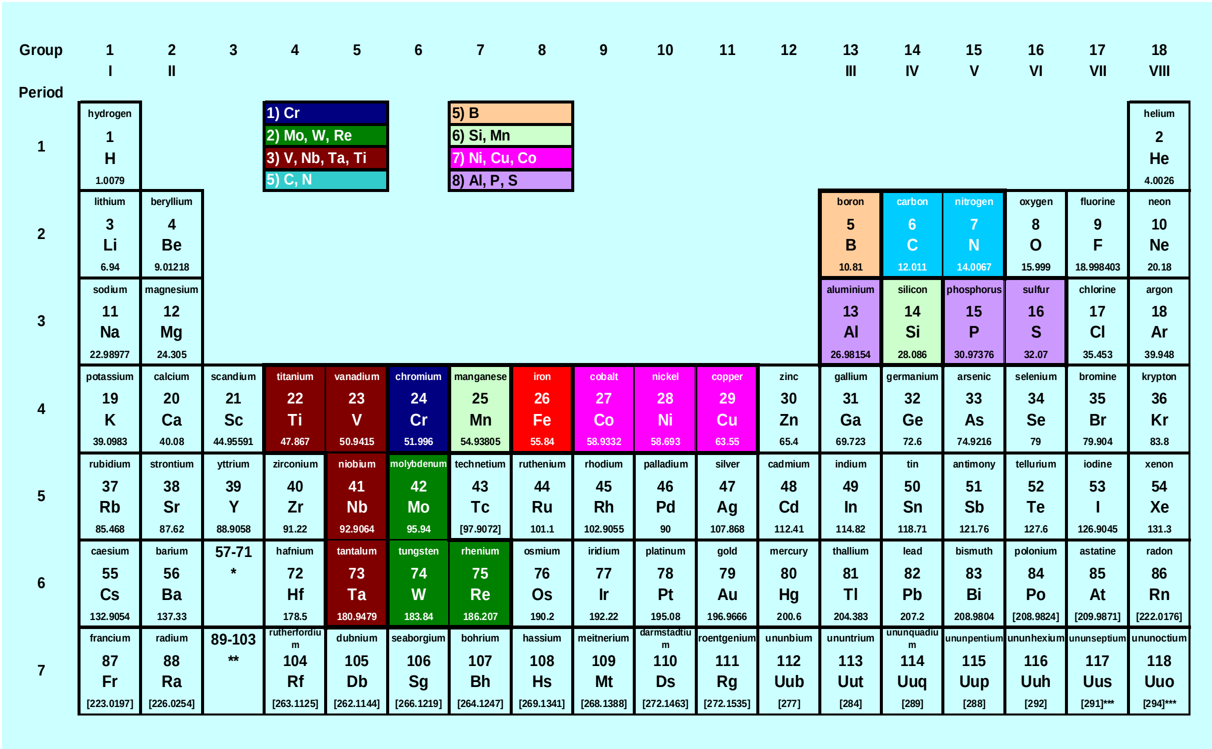
high temperature capability REDUCED

Strengthening Mechanism of FMS



- Effect of **B** addition
- Optimization of **C, N**
- Optimization of **Nb**
- Effect of **Ta** addition

Evaluation of Minor Element Effect



1) Cr: Precipitation hardening
2) Mo, W, Re: Solid solution hardening
3) V, Nb, Ta, Ti: Precipitation hardening
4) C, N: Precipitation hardening
5) B: Stabilization of precipitates
6) Si, Mn: Stabilization of precipitates
7) Ni, Cu, Co: Stabilization of microstructure
8) Al, P, S: Stabilization of microstructure

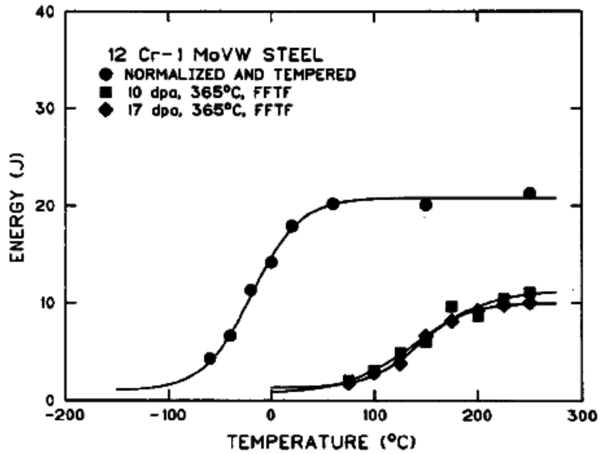
Evaluation of base data

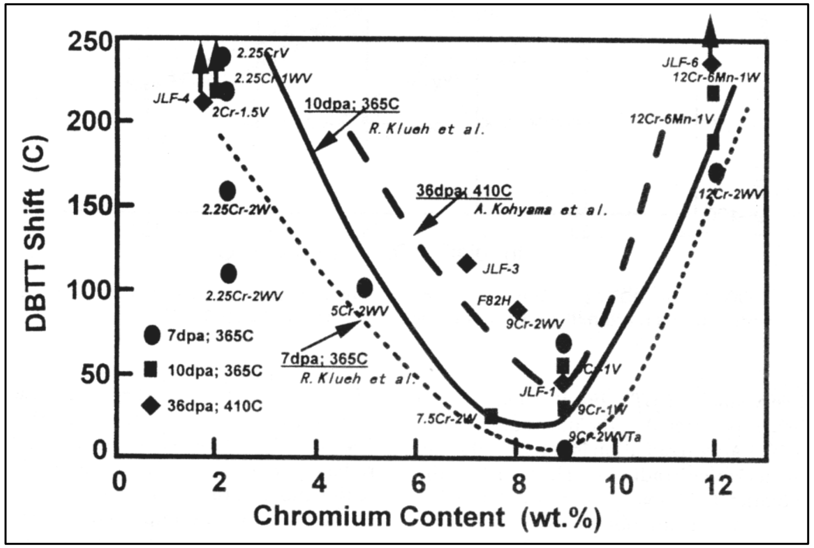
- Crystal structure/atomic radius
- valence/Electronegativity/MP
- nucleus embrittlement
- Formation of δ-ferrite
- Phase transformation temp. (M_s, A_1)

MAIN PROBLEMS

- HIGH TEMPERATURE LIMIT

- EMBRITTLEMENT

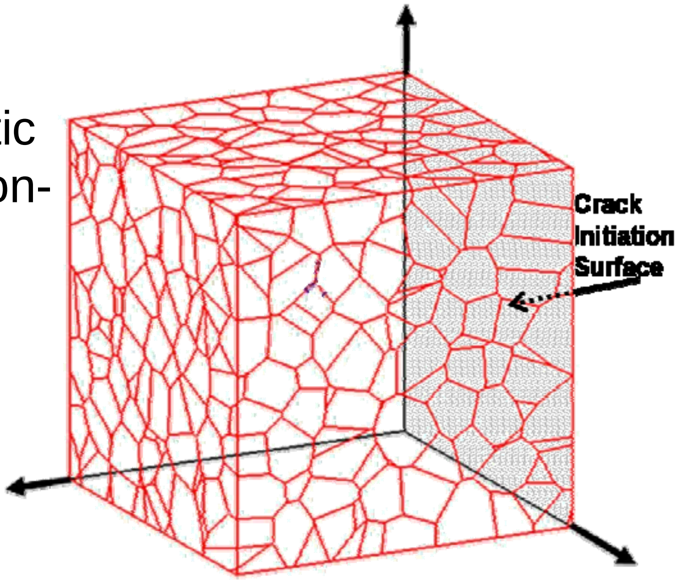




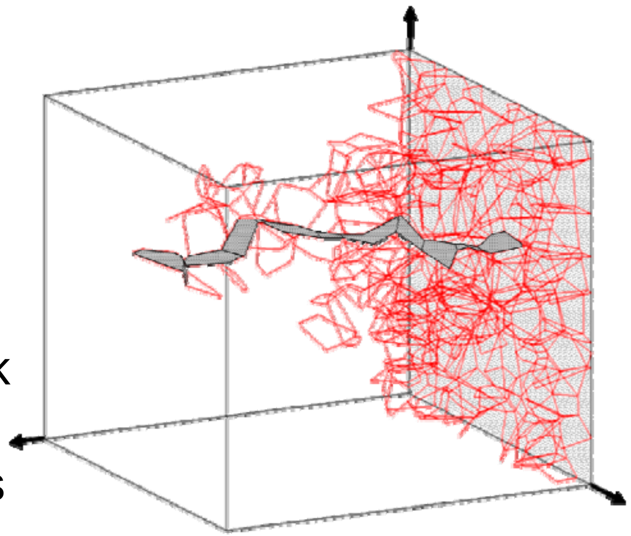
Charpy impact curves of HT9 (12Cr-1MoVW)
in the unirradiated condition and after irradiation
to 10 and 17 dpa at 365 ºC in FFTF.

Figure 1: Intergranular crack connectivity in a simulated Grain structure

(a) Schematic of Poisson-Voronoi Grain structure



(b) Illustration of crack percolation along weak grain boundaries



(c) Percolation probability vs % of crack resistant/strong grain boundaries

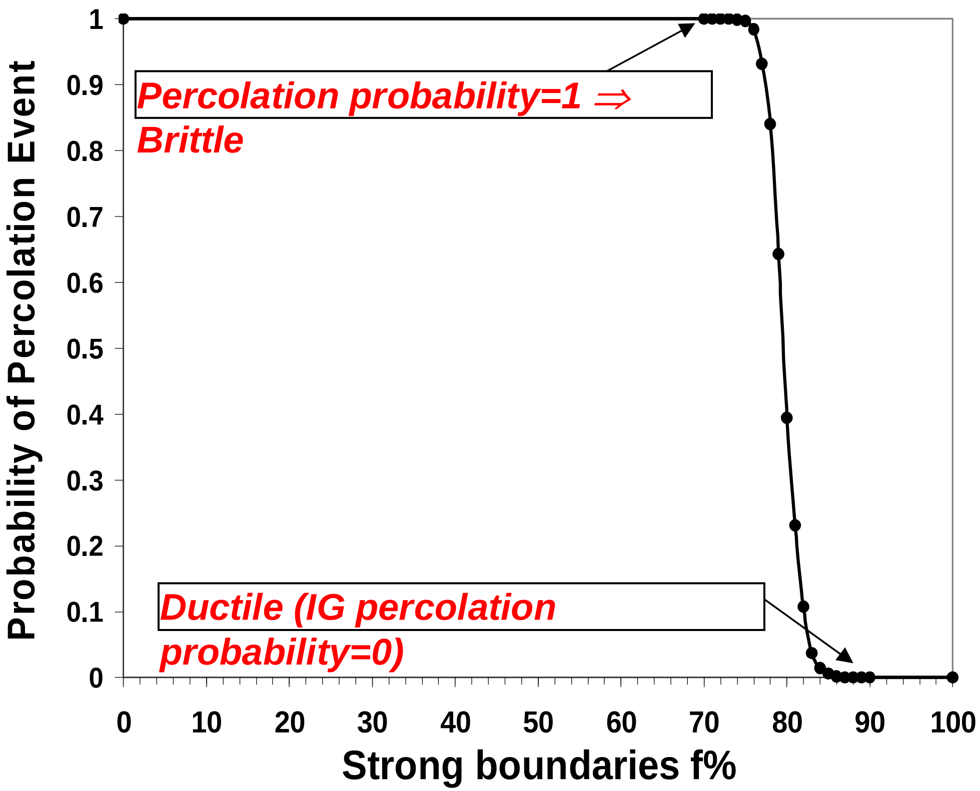
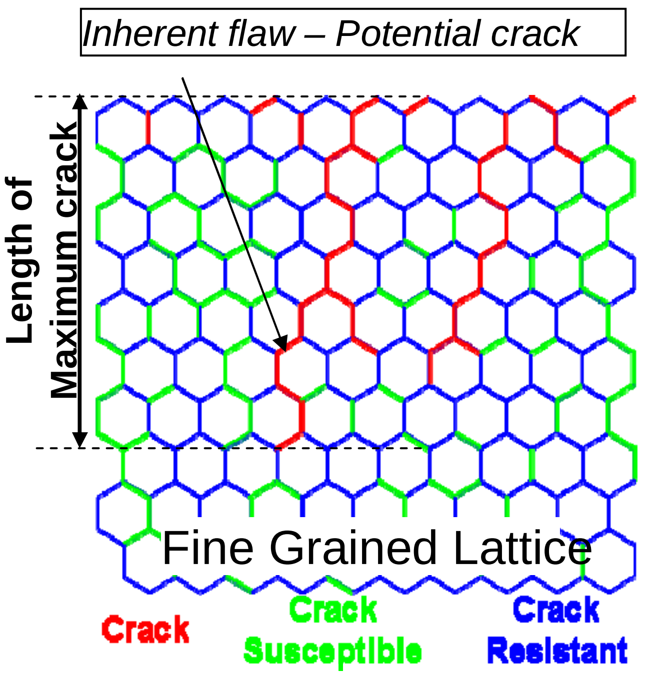
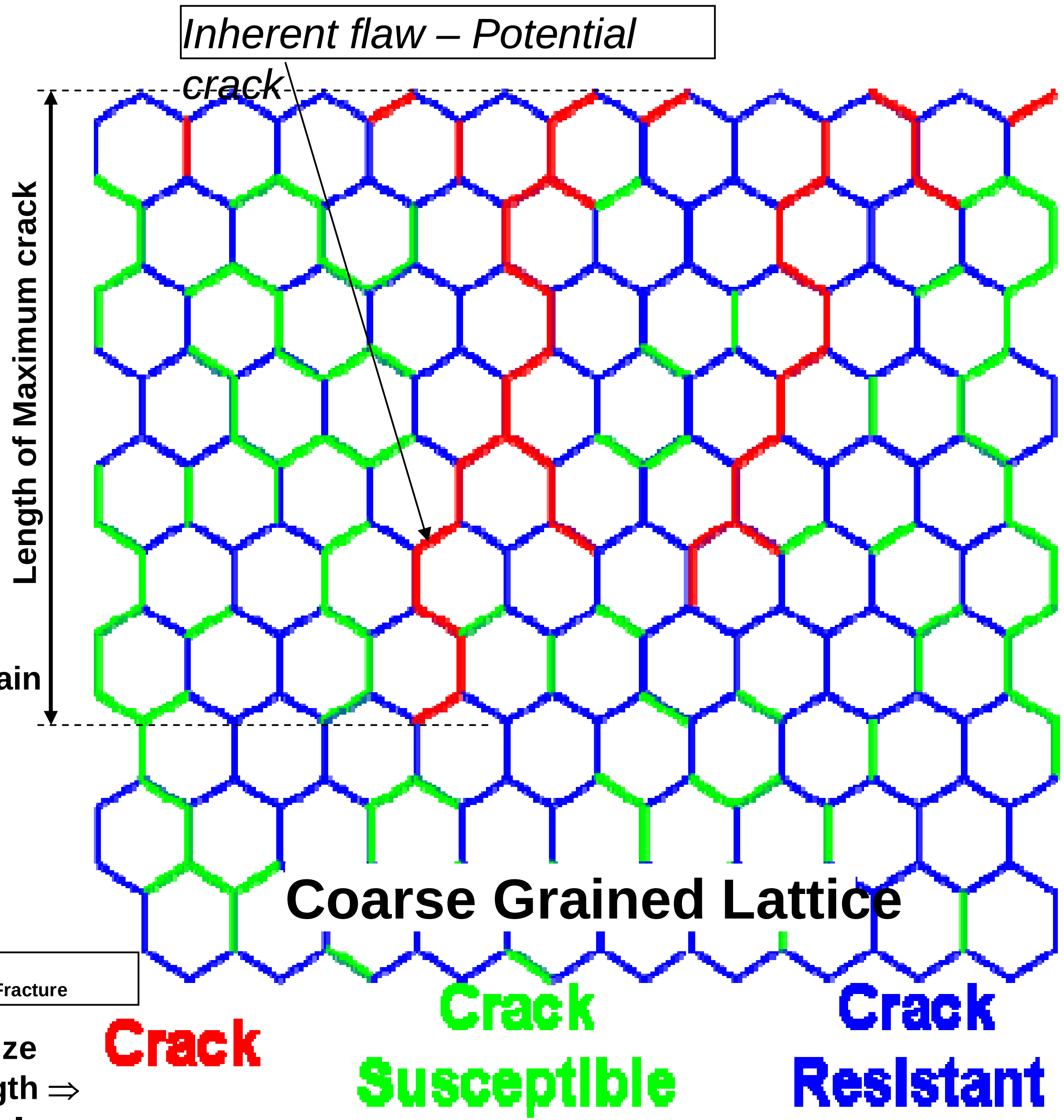


Illustration of grain size effect on length of potential crack





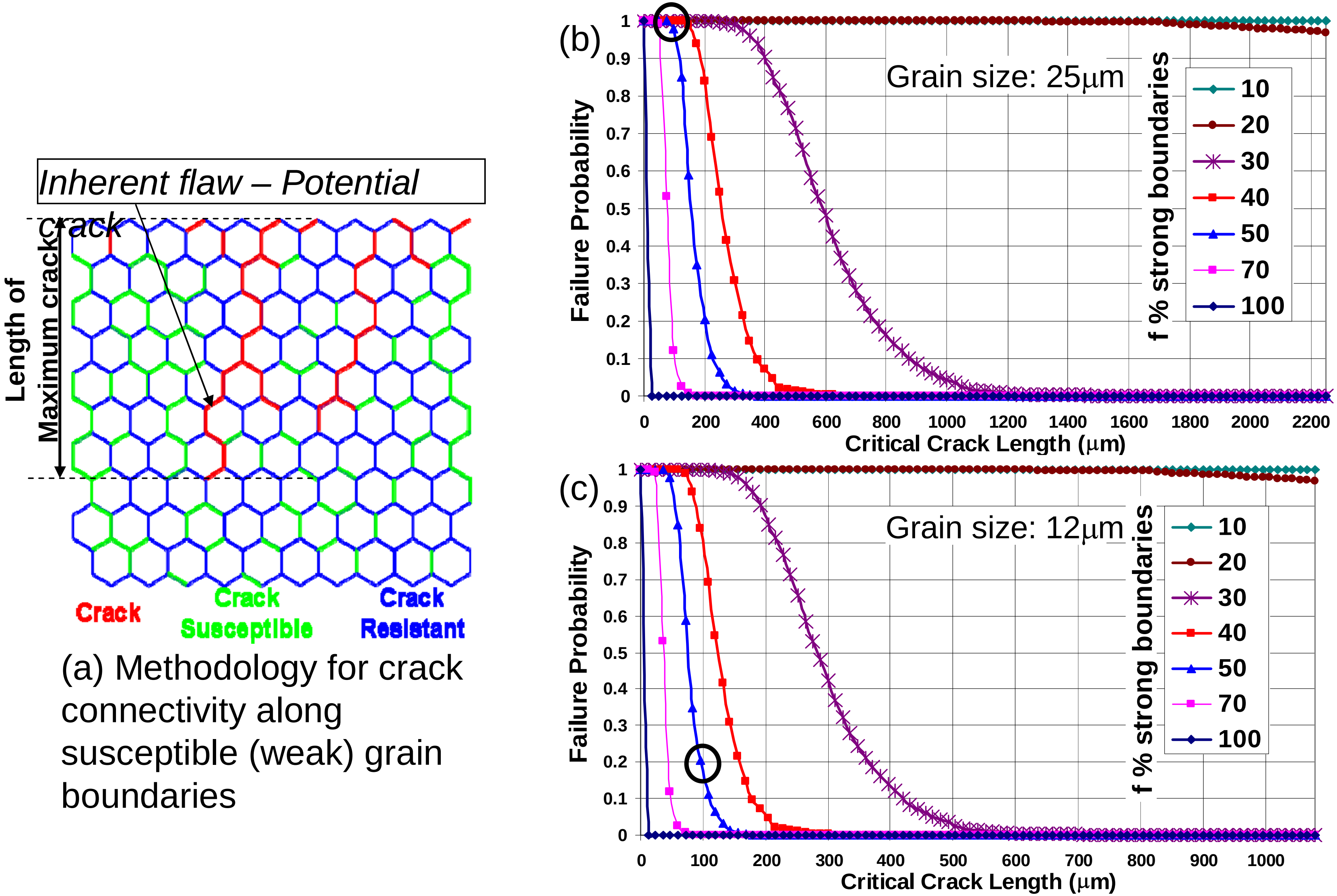
For the give percentage of crack resistant boundaries, crack size in grain units is same, but in length units, is scaled by the factor of grain size ⇒ Length of potential inherent flaw is more in coarse grained structure

Condition for Brittle failure:

Crack length $_{\text{Potential}}$ > Critical crack length $_{\text{Fracture Mechanics}}$

Fore all values of f, smaller grain size gives a smaller potential crack length ⇒
small grain size is beneficial

Figure 2: Intergranular crack connectivity in a simulated Hexagonal Grain lattice



(a) Methodology for crack connectivity along susceptible (weak) grain boundaries

* For **critical crack length of 100μm** and **50% strong boundaries**, the failure probability for coarse grained (**25μm**) structure is **~0.99** compared to **0.2** for a fine grained (**12μm**) structure

250 dpa with temp. capability up to 600 & more ????

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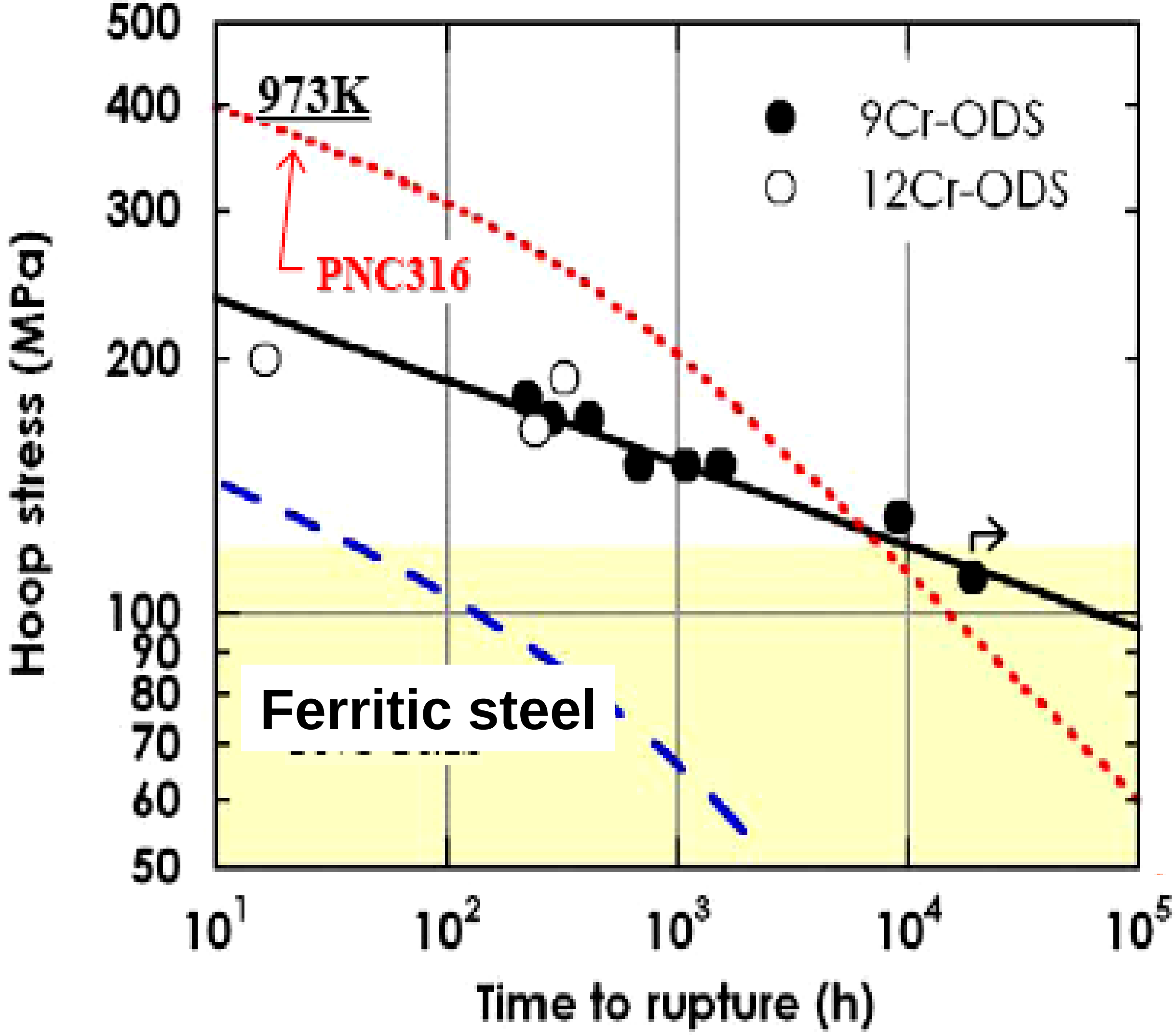
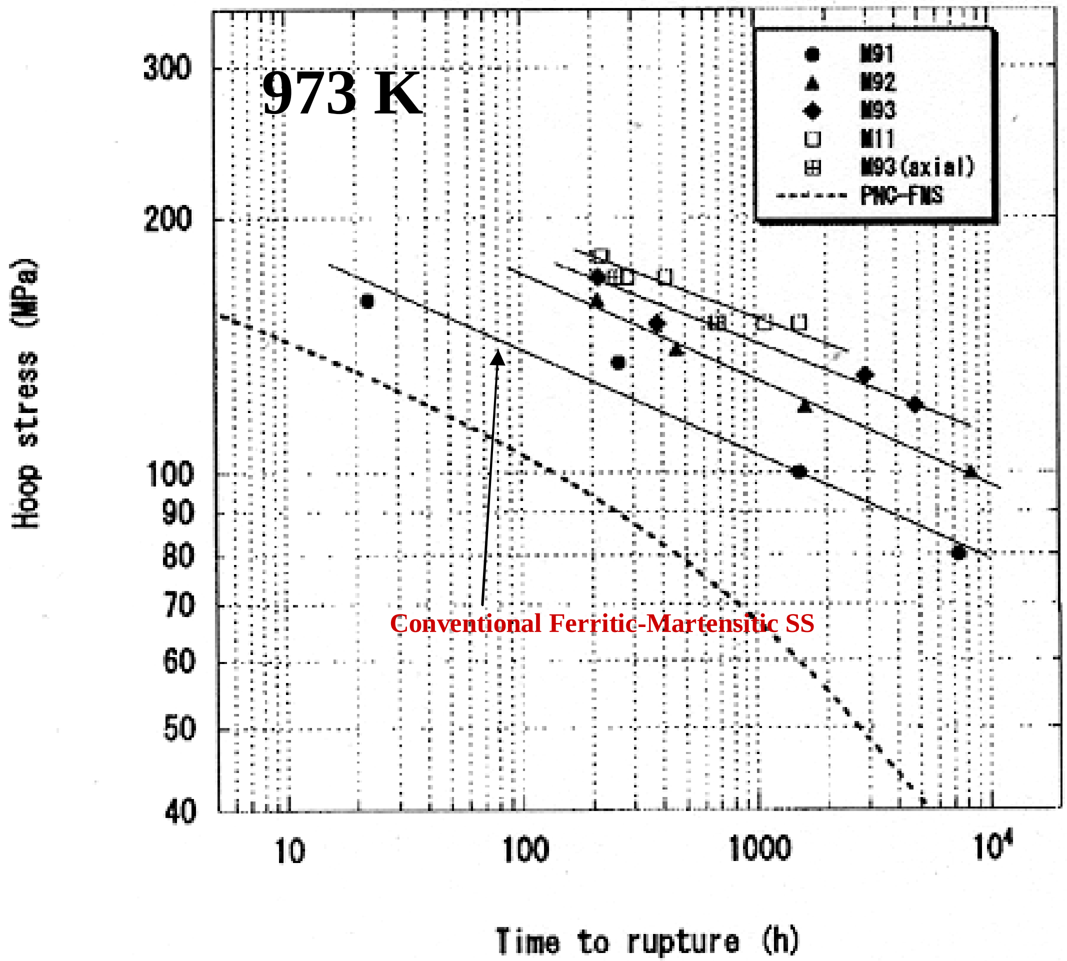
9Cr-ODS steel

9Cr-0.24 % Y_2O_3



9Cr ODS Martensitic Steel Claddings

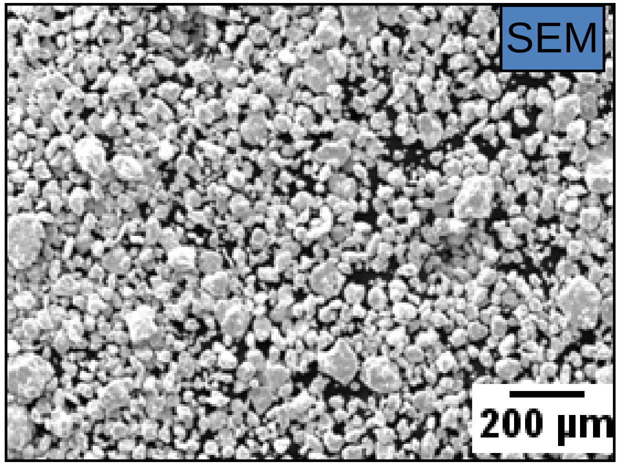


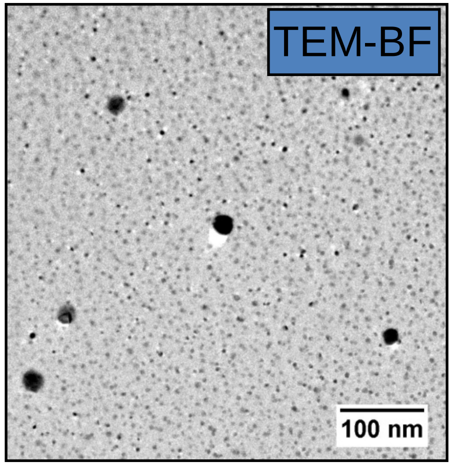
- **Better creep strength than ASS**
- **DBTT is close to room temperature**
- **No carbon leaching in sodium environment**
- **Ferritic structure provides better resistance to neutron damage and has better void swelling resistance. (Compared to austenitics)**

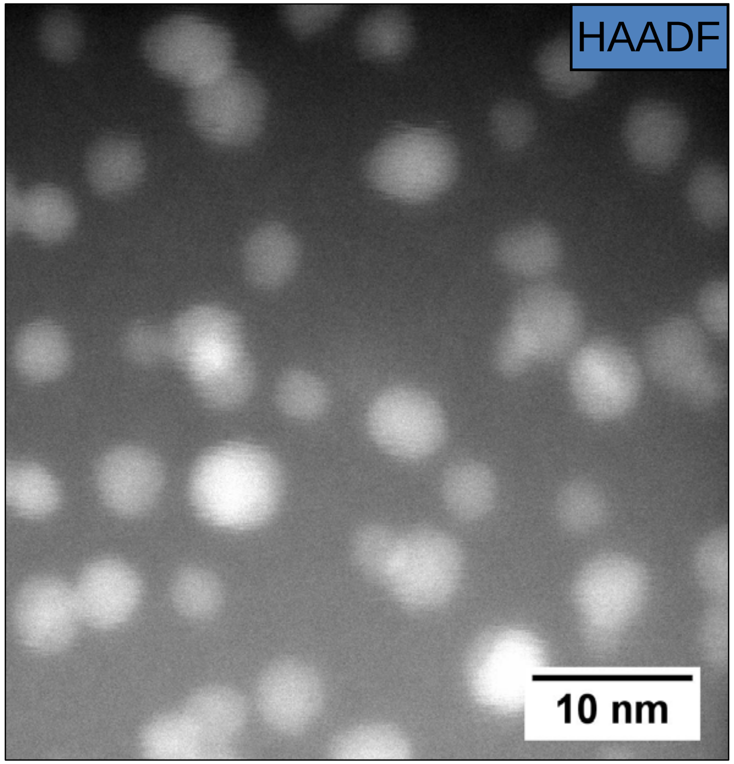
Creep strength increases with increasing Ti content from 0.1(M91) to 0.2 (M93) wt% and Y_2O_3 from 0.30 (M92) to 0.37 (M11) wt%

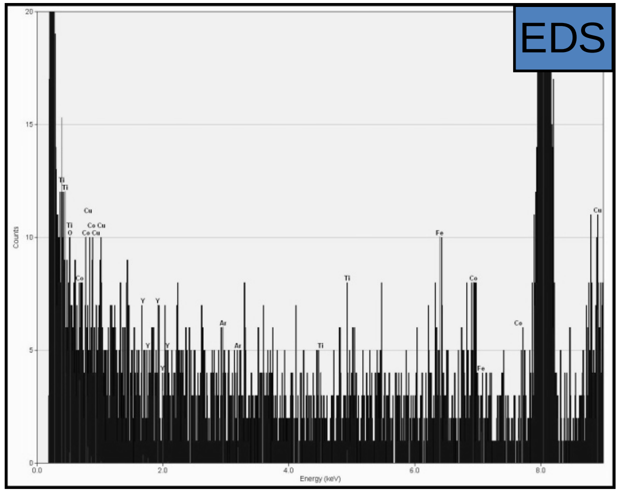
S. Ukai, S. Mizuta, M. Fujiwara, T. Okuda and T. Kobayashi, J. Nuclear Science and Technology, 2002, Vol. 39, No. 7, pp. 778-788.

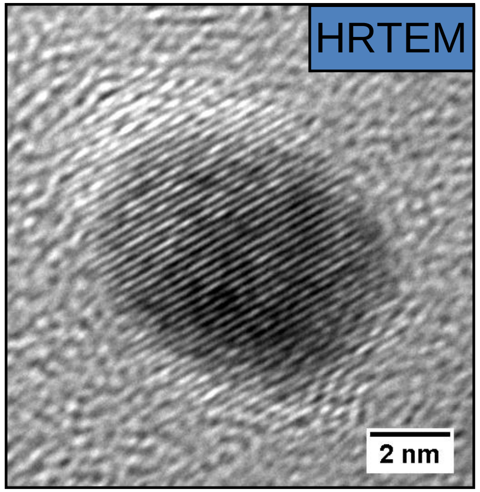
ODS Steels for future FBR Applications





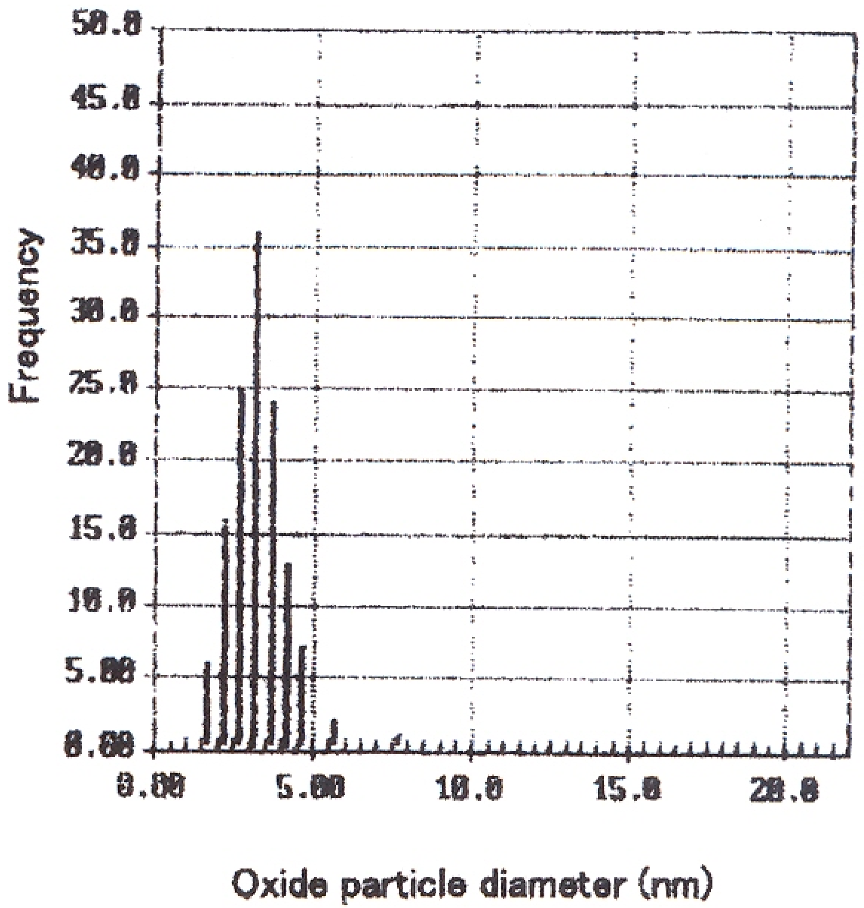




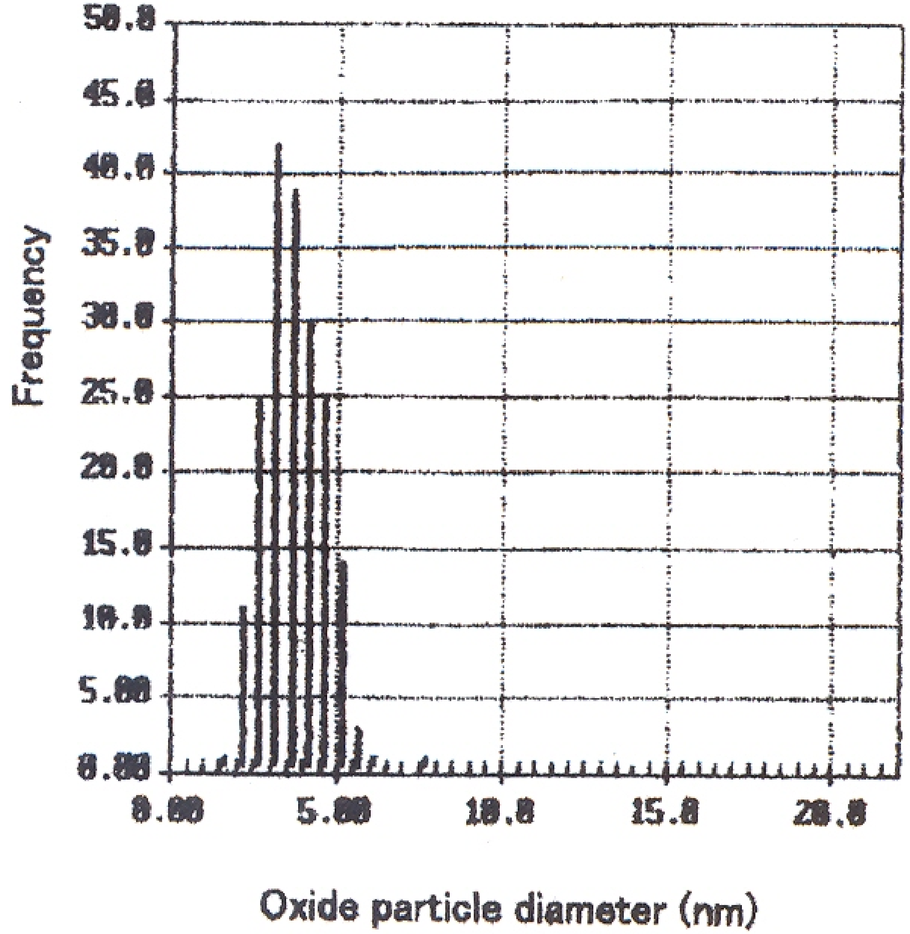


Qualitative *Z*-contrast for detection of microchemistry variations

Effect of Ti and Y_2O_3 on dispersive particles distribution

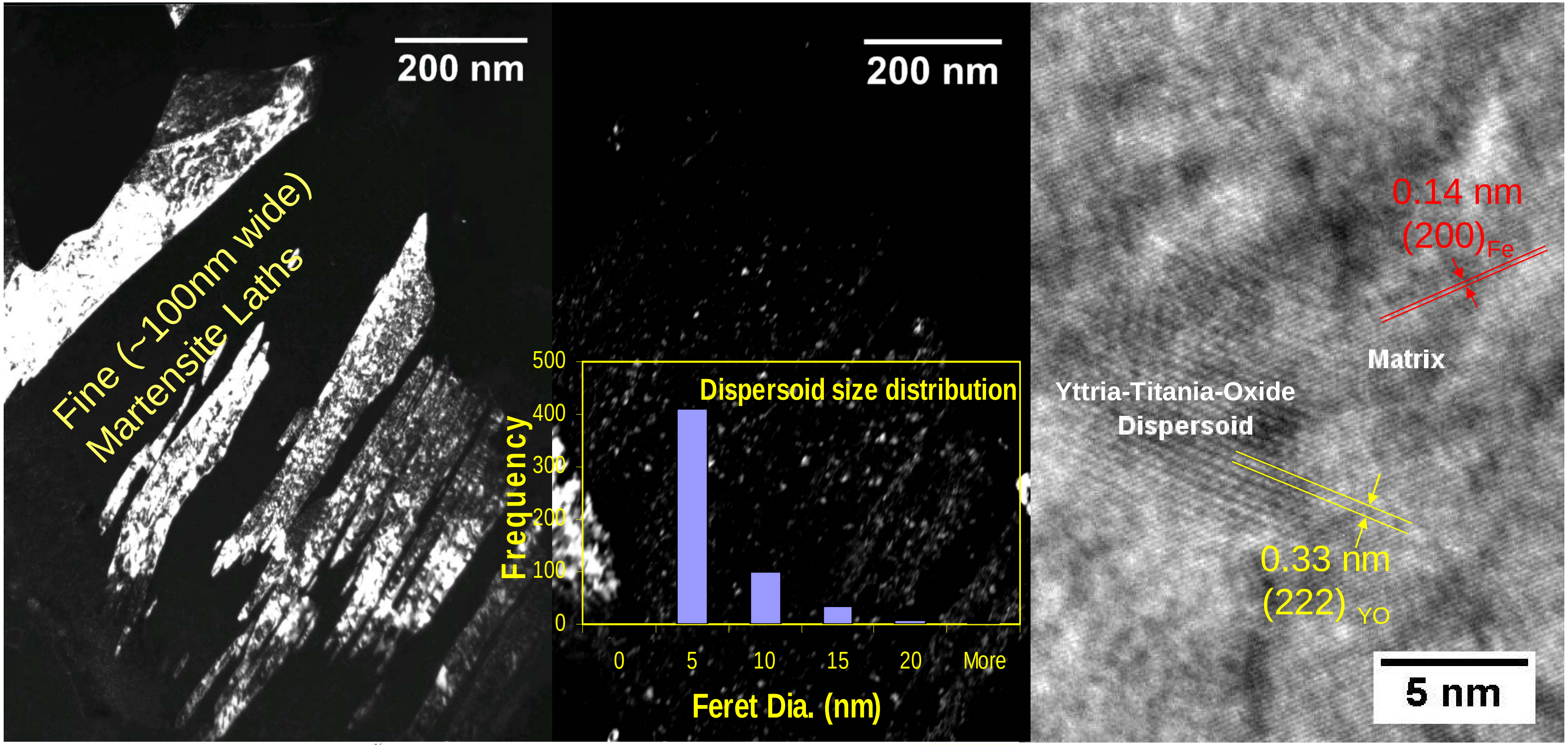


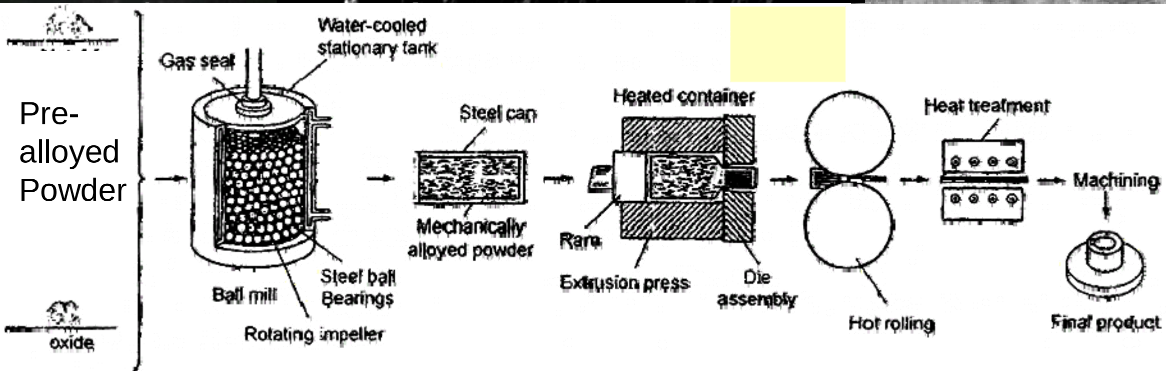
Ti – 0.20, Y_2O_3 – 0.30 (wt %)



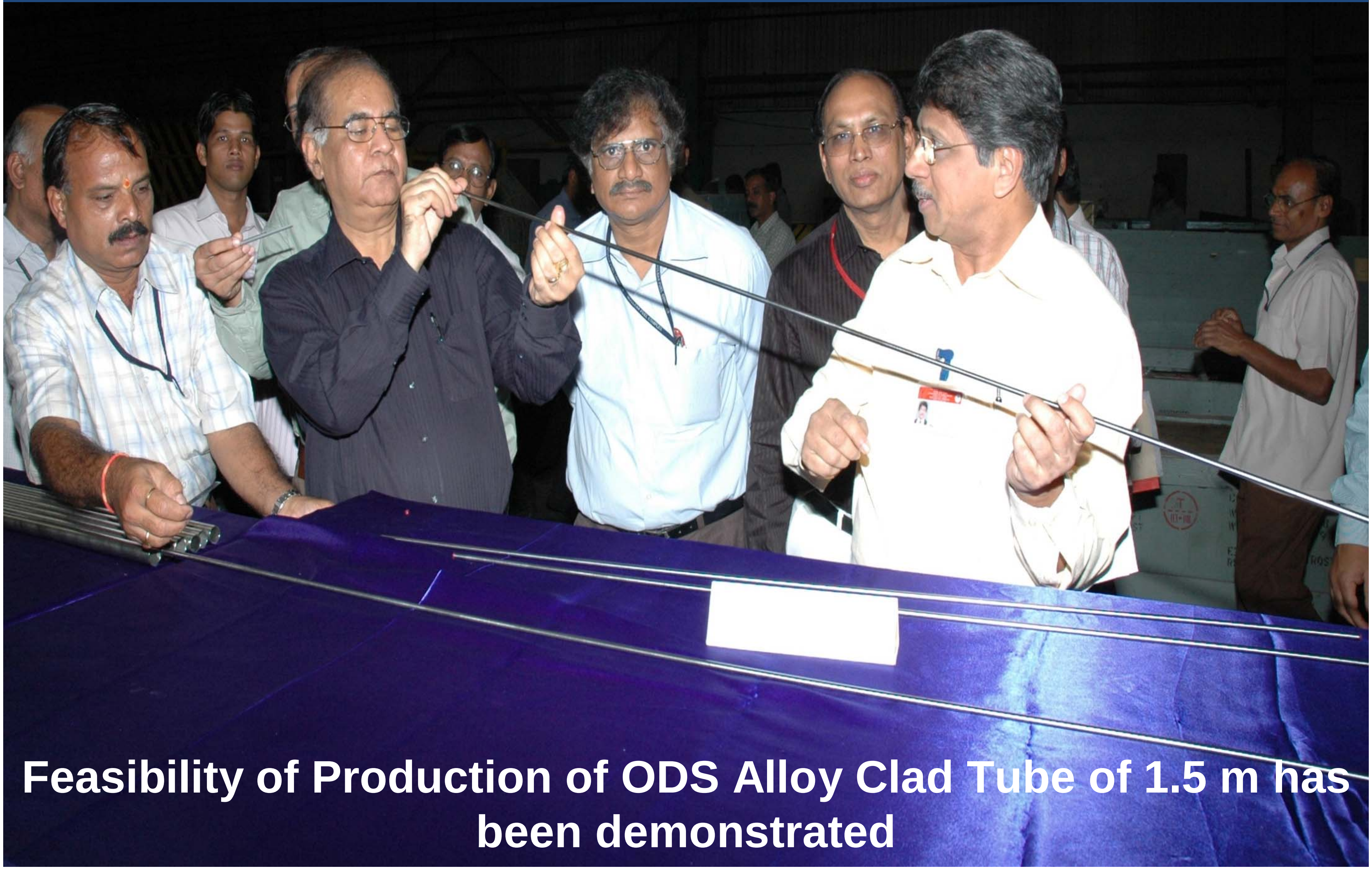
Ti – 0.20, Y_2O_3 – 0.35 (wt %)

Indian ODS:
Fe-9Cr-2W-0.2Ti-0.35Y_2O_3-0.16C (MA / Extruded at 1050^oC)



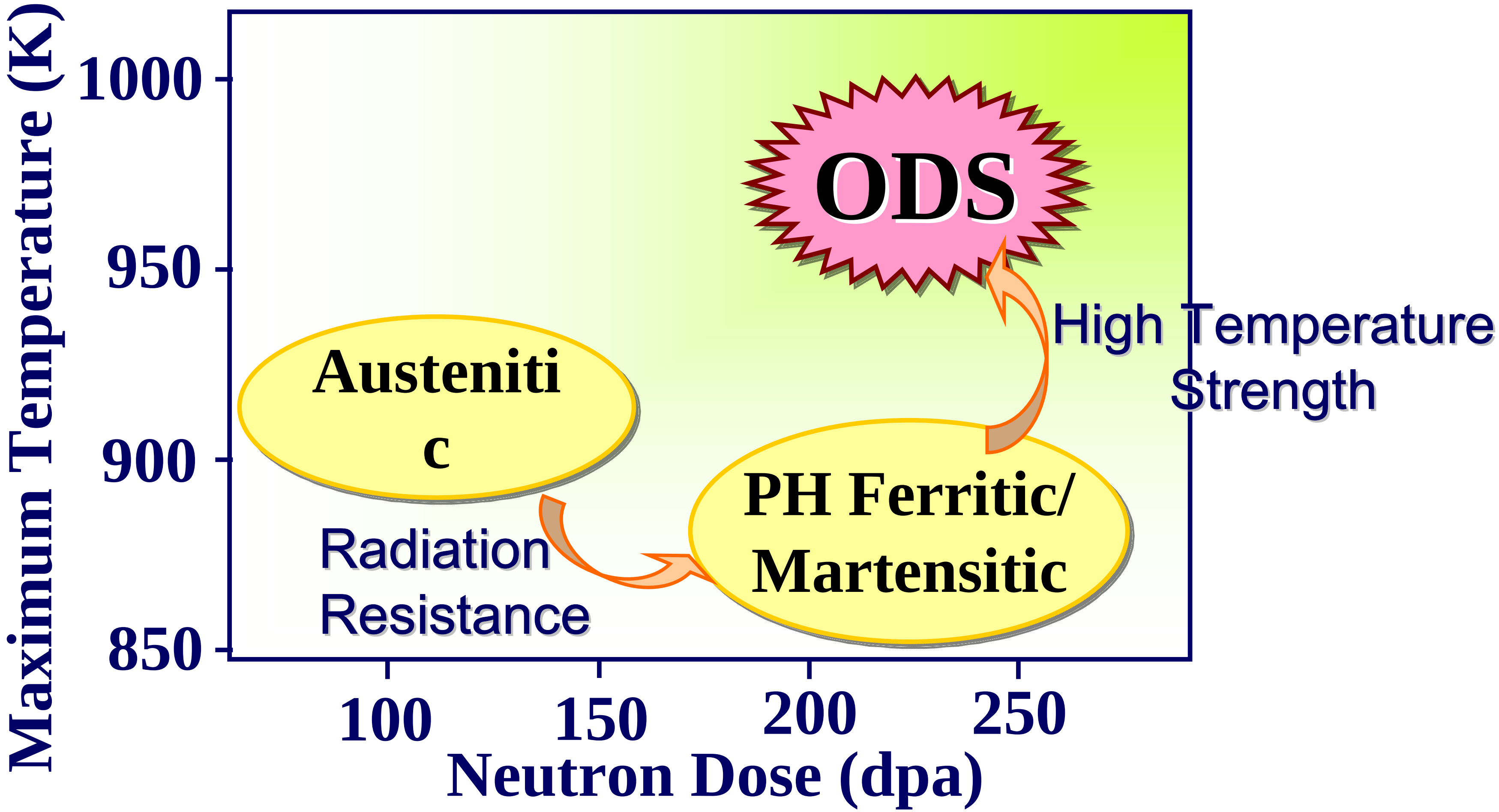


VISUAL INSPECTION OF ODS CLAD TUBES AT NFC, HYDERABAD



Feasibility of Production of ODS Alloy Clad Tube of 1.5 m has been demonstrated

γ Alloys to α alloys to ODS

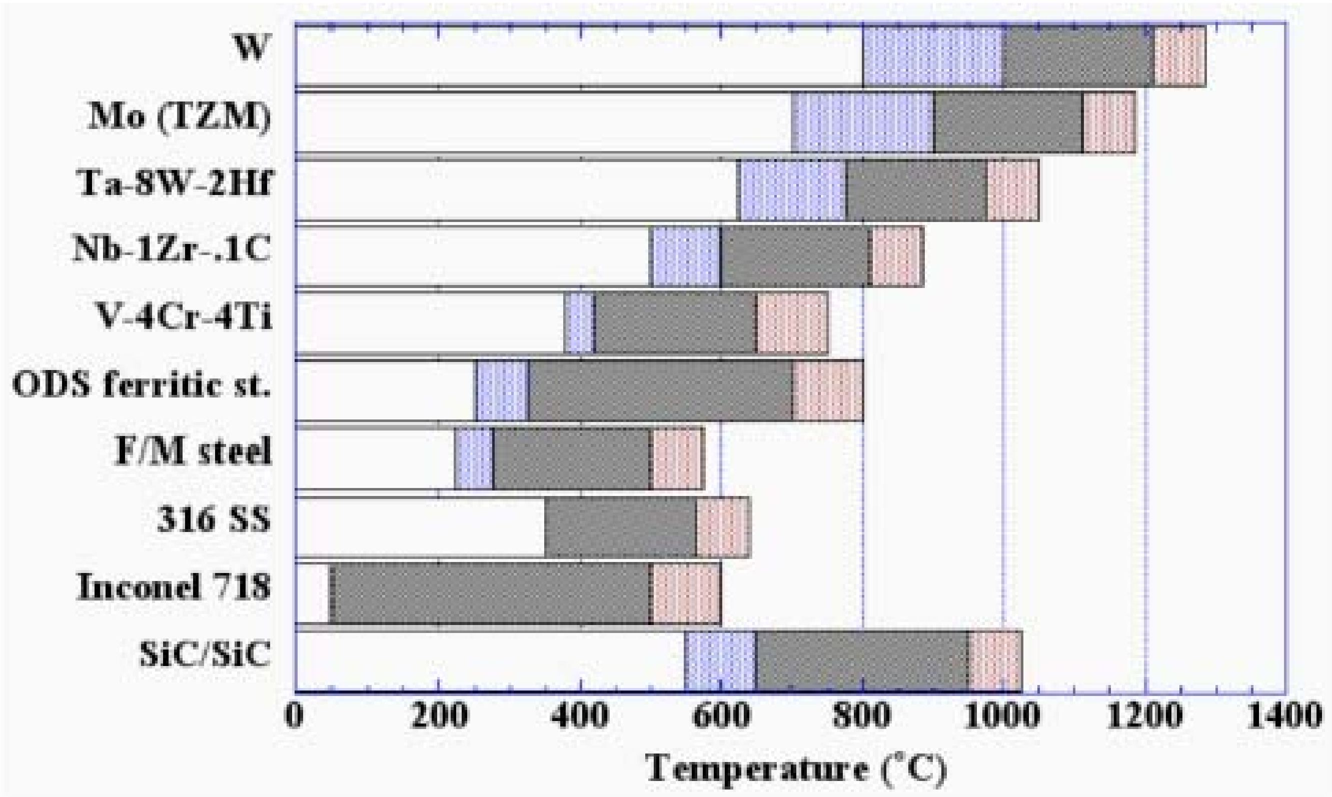


Precipitation hardening will be lost in ferritic steels over 923 K.

↓

Oxide dispersion strengthening will be effective even over 973 K.

HIGH TEMPERATURE MATERIALS



THANK YOU VERY MUCH FOR YOUR PATIENT LISTENING;

mvl@igcar.gov.in - for any further contacts or clarification