ATR National Scientific User Facility
Users Week 2010
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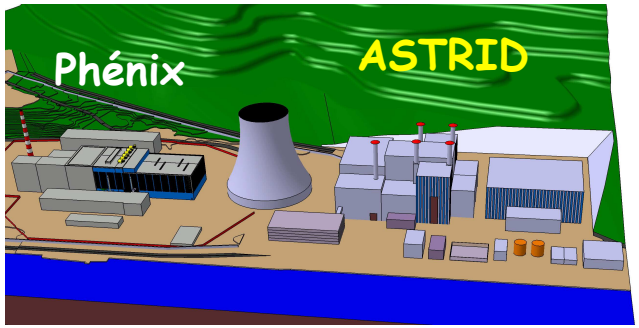
Fast Reactor Materials

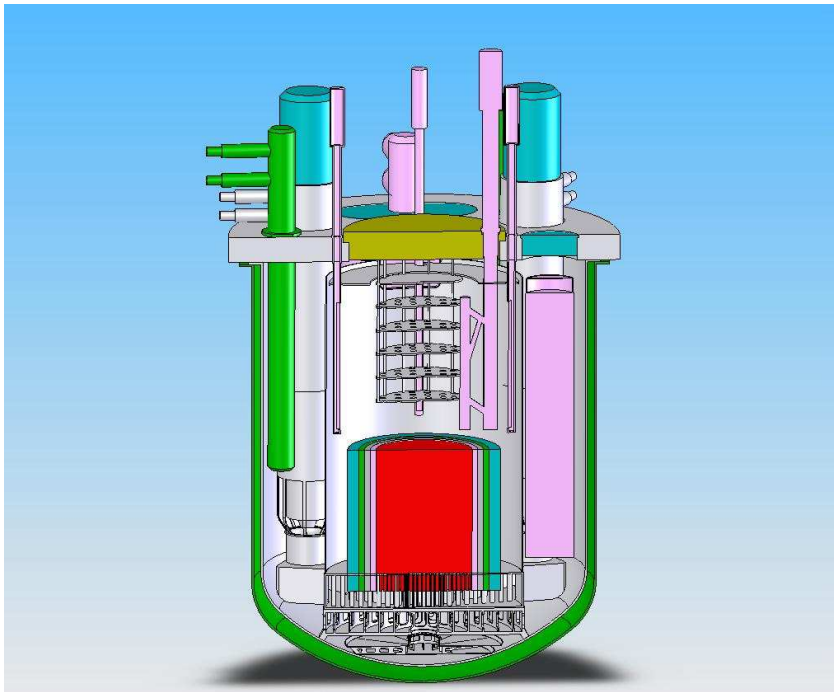
Y. de Carlan - Ph. Dubuisson



Two SFR concepts

Basic characteristics :

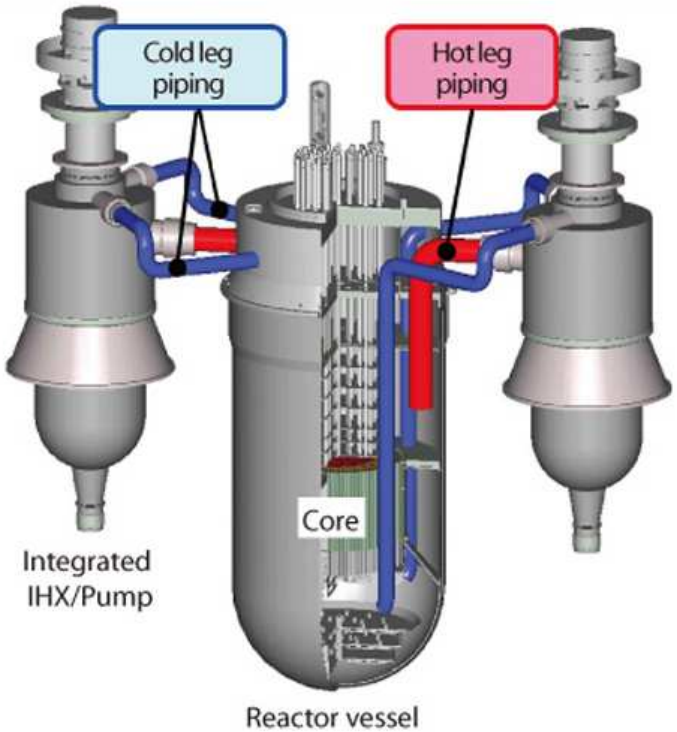
- ***isogenerator core without cover (not a fast breeder reactor)***
- ***innovative system to limit the problems due to the Na/H_2O heat exchanger gas, alternative fluid…)***



Pool reactor

EFR + simplifications + innovations + inspections

-> exchanger Na - N_2 or CO_2 or Pb-Bi or…)



Loop reactor

Vessel is smaller

heat exchanger are out of the vessel

SFR – Main components

Life time
to design
30 → 60 ans
5 10^5 h

1000 MWe
Pool type
Modular SG
AREVA design

Steam Generators, Heat Exchangers
350 – 525°C
lds, Compatibility
d Na – H_2O

9 Cr
800H
316 LN
All. Ni

316 LN
800H
Ni alloys

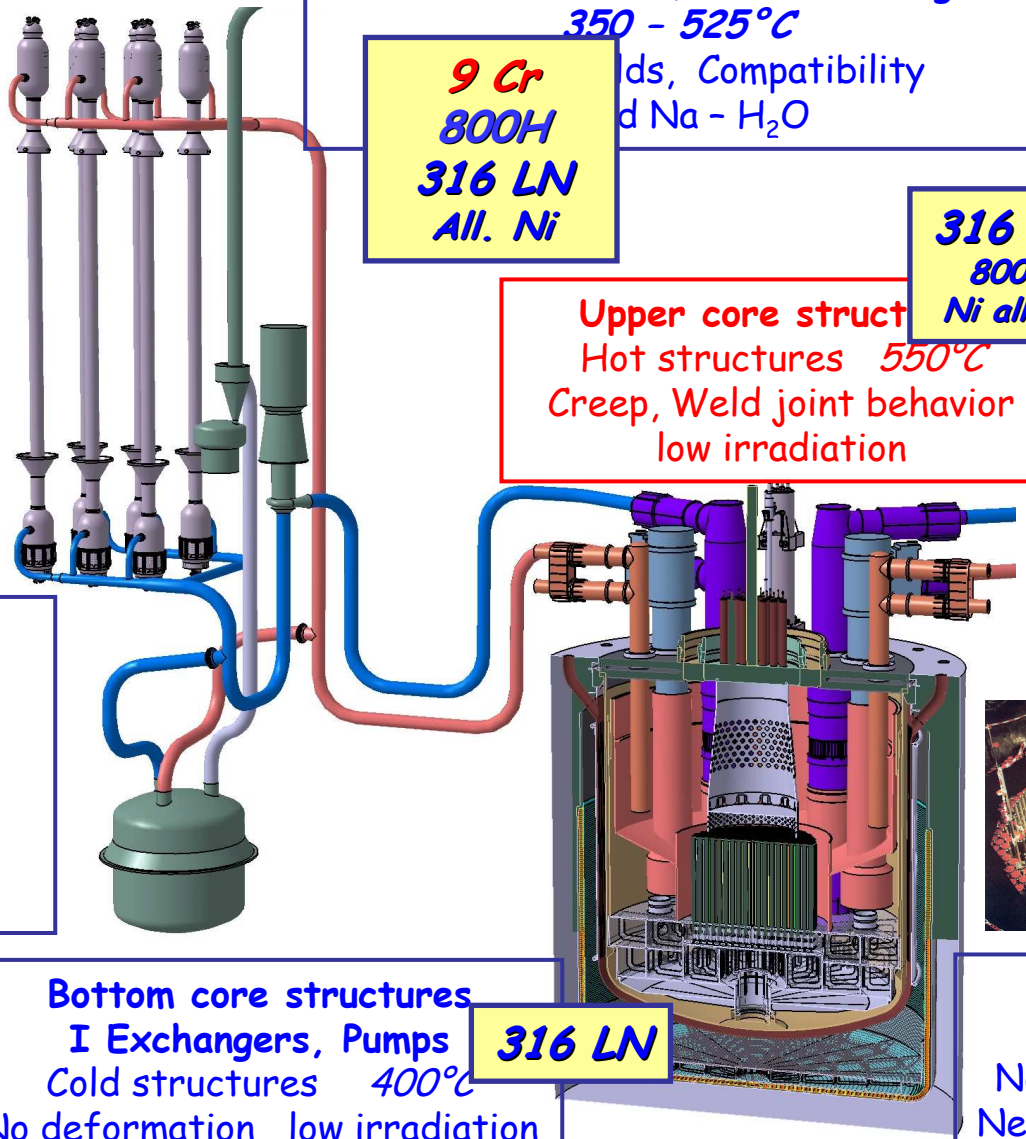
Upper core struct
Hot structures *550°C*
Creep, Weld joint behavior
low irradiation

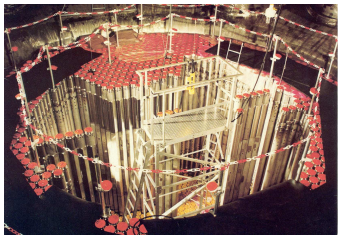
9 Cr
F/M ODS
Adv. Aust.

Core
Sub-assemblies
400 – 650°C
Irradiation

9 Cr
316 LN

Circuits - Pipes
350 – 550°C
Creep, fatigue,
creep-fatigue,
thermal fatigue,...
Aging
Welds





Bottom core structures
I Exchangers, Pumps
Cold structures *400°C*
No deformation low irradiation

316 LN

Vessel
400°C
No deformation
Negligeable creep

316 LN

Requirements and Material choices

- **Requirements**
  - **Ageing** *temperature, duration, mechanical and thermal sollicitation*
    - *Mechanical behavior* creep, fatigue, creep-fatigue, DBTT, toughness,…
    - *Weldability and aging of welds*
    - *Compatibility in different environment Na, H_2O-vapor,*

60 years
400 – 550°C

  - **Irradiation** Core Cover Plug - Diagrid
    - *Nominal conditions* *Mechanical behavior* *embrittlement,…*
    - *Transient conditions* *incidental and accidental*

316 LN
9 Cr
800 H
~~Ni alloys~~

  - **Reduce Activation in circuits and components**
    - *Suppress all alloys with Co content* *Coating, Valves,…*
    - *Limit use of Ni alloys (Ni → Co)*
    - *Reduce impurities content in steels* *Co, Ni,…*

Core components
Primary Circuits

- **Feedback from Fast Breeder Reactors and previous R&D programs**
  - **316 L(N)** *Fe-17Cr-12Ni Mo Si* *0,02 C* *0,06 N* **800** *Fe-30 Ni-15CrTiAl*
    - *Good experience – Large R&D available*
    - *Good high temperature properties, welding*

30 → *60 years*

  - **Investigations of components from Fast Neutrons Reactors**
    - *Na leak → Modification in design or in materials*
    - *To obtain long term data* *35 years for Phénix*

Phénix
Superphénix

→ **R&D Program on Martensitic 9Cr steels**

Martensitic 9Cr steels applications

- **Interest of FM Steels**
  - *Thermal coefficient of conductivity*
  - *High thermal dilation coefficient*
  - *Good mechanical properties at moderate temperatures*
  - *Manufacturing cost*

- ***9 Cr steels***

Fe 9Cr 0.1 C
1Mo(W)
Si V Nb

Grade 91
Grade 92,…
News alloys

Reference material
Creep improvment due to W, B additions ~~Co~~
Study to develop new martensitic steels optimized for ***creep properties***

International programs

- ***Mechanical pr***

Improvment *in toughness*

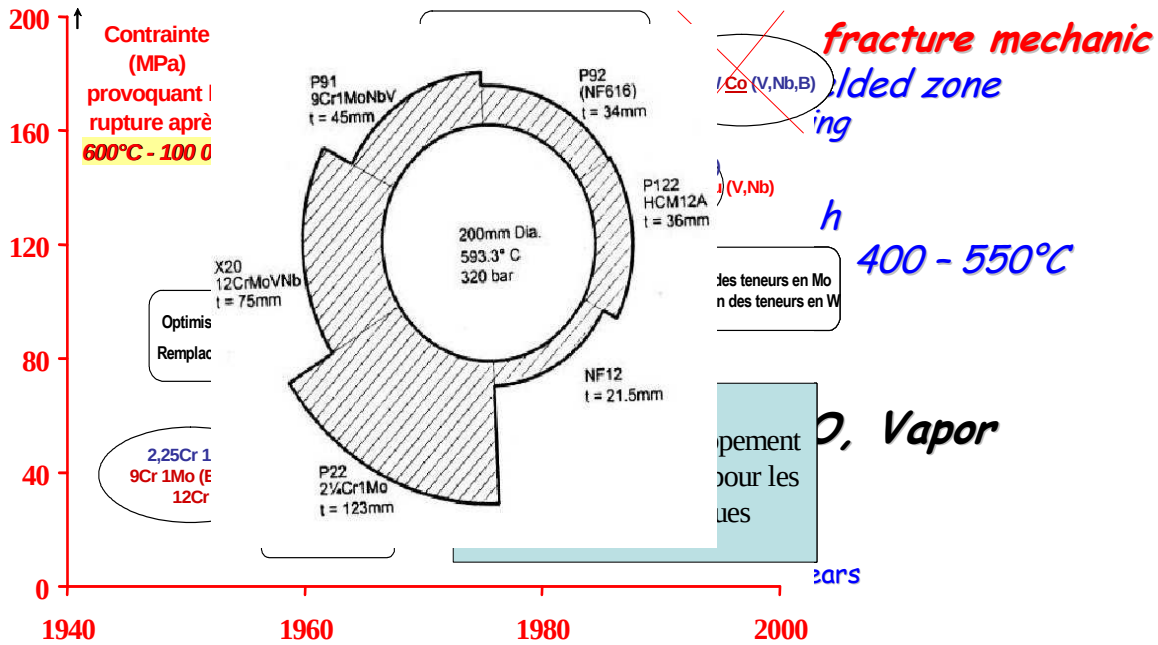
- ***Aging***

predict the
"Mo

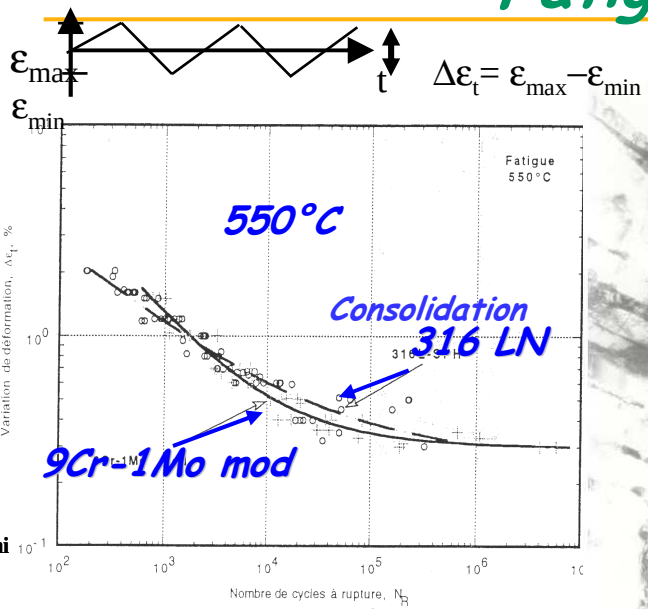
- ***Weldability***

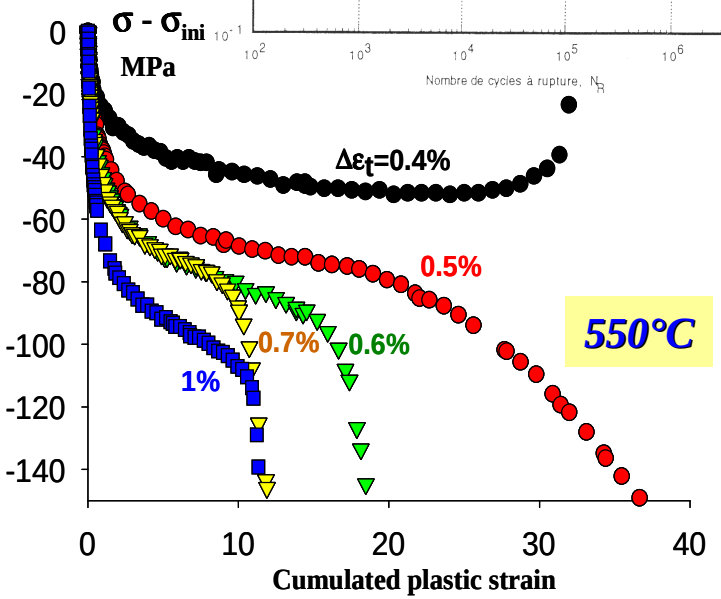
316 LN
Ni alloys

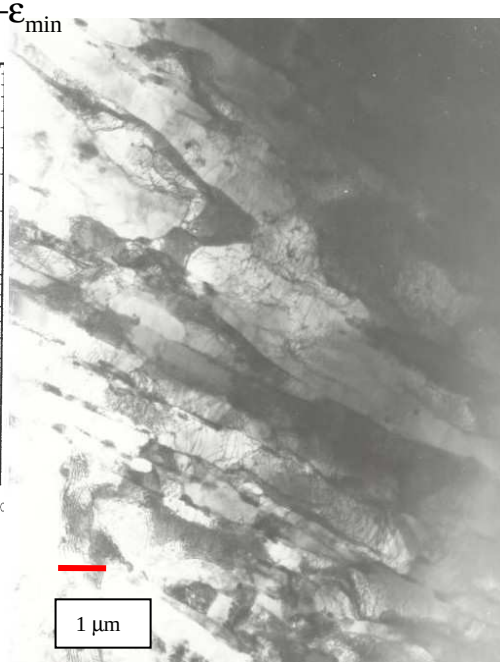
- ***Liquid and ma***
  - *impurity effe*
  - Inspection of



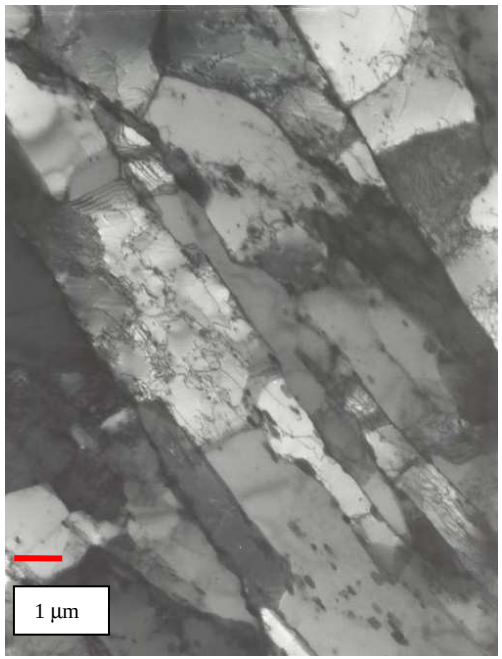
Fatigue of 9Cr steels







Initial microstructure



1000 cycles $\Delta\varepsilon$ = 1%
10 h

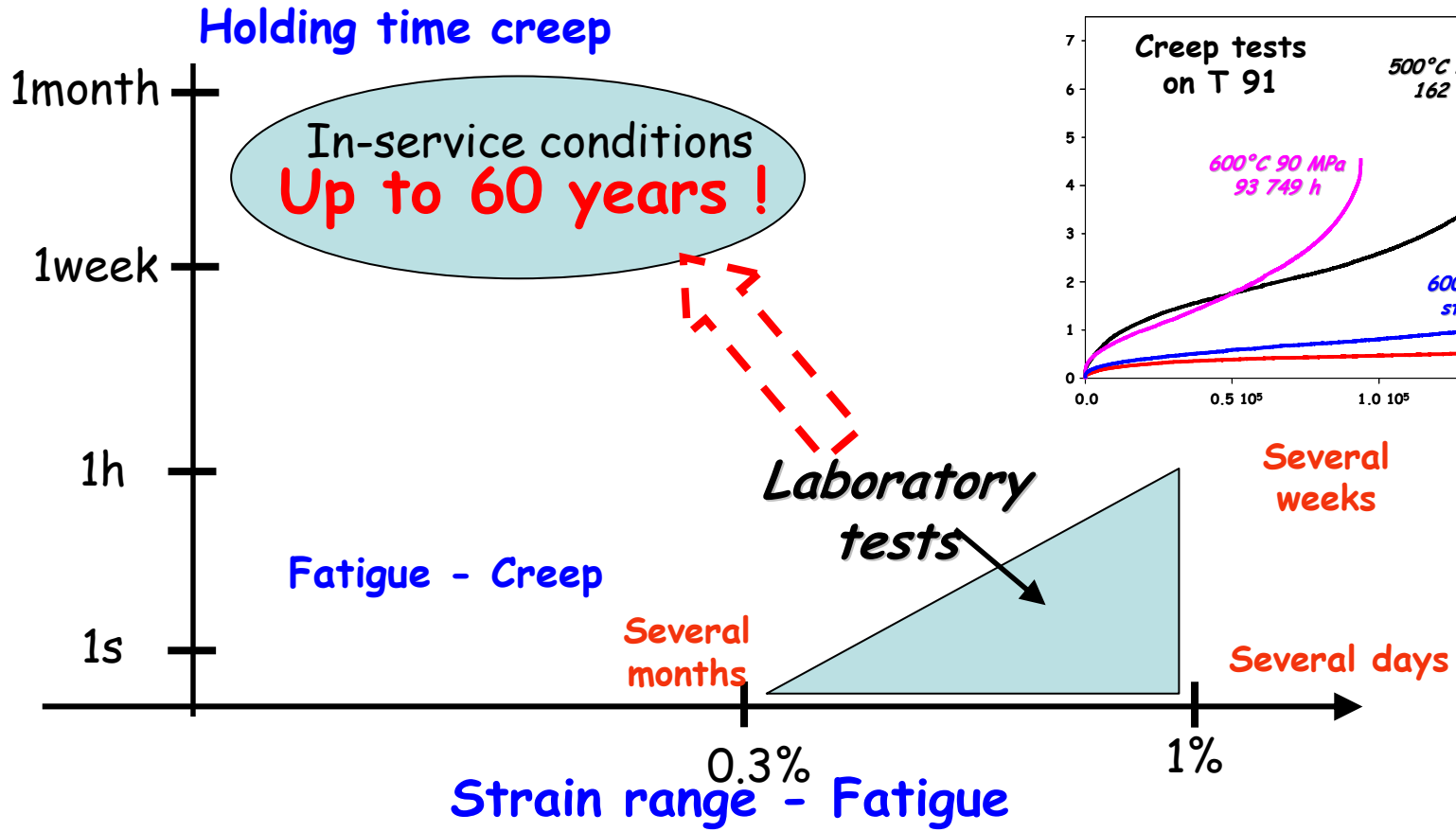
- Coarsening of the microstructure ➔ equiaxed
- Annihilation of Low-Angle Boundaries inside subgrains
- Annihilation of dislocations

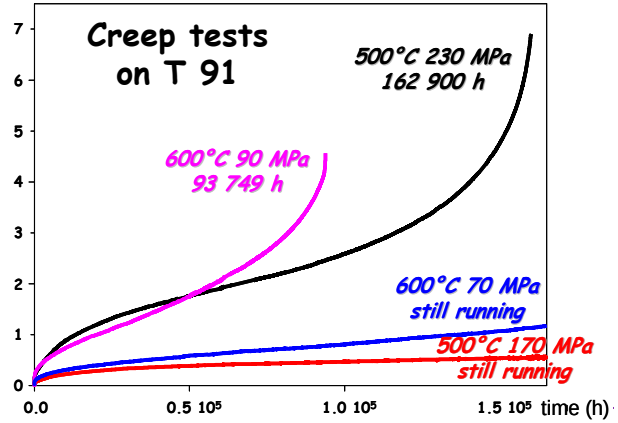
Cyclic softening of T91 steel

Enhanced modelling

Climb-assisted annihilation between mobile dislocations and LAB dislocations

Creep – fatigue





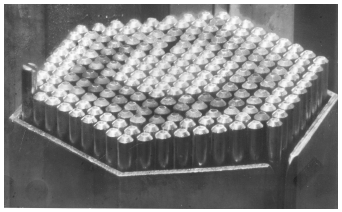
Extrapolations of mechanical data up to 60 years

Extrapolations of the laboratory fatigue life data for the prediction of very long term in service lifetimes

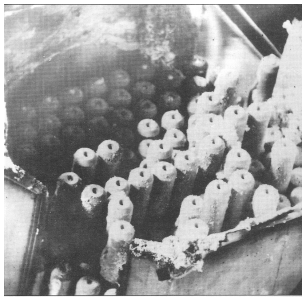
Understanding the mechanisms responsible for aging, creep, fatigue, damage, fracture,…

Materials for SFR subassemblies

Wrapper – Fuel pin Cladding materials
From Austenitic steels to ferritic-martensitic steels



irradiation



- **Austenitic steels**
  - Swelling and mechanical properties
  - 15-15 Ti → Advanced Austenitic steels
    - *Limit of these steels for core applications*

- **Ferritic-martensitic steels**
  - Martensitic 9Cr steels 9Cr-1Mo, 91, RAFM
    - *Only for wrapper application*
  - Materials for cladding application
    - *Oxide Dispersion Strenghtened steels*
      - Elaboration
      - Properties before irradiation
      - Behavior under/after irradiation

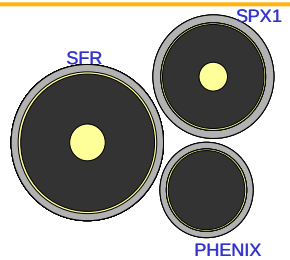
Thermal creep

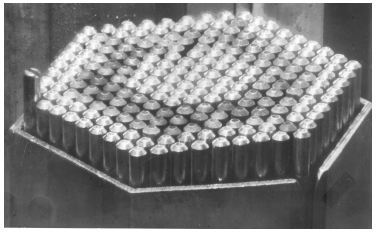
Weldability
Mechanical properties
Environmental behaviors
Charged particles irradiation

SFR – Cladding – Requirements and material choice

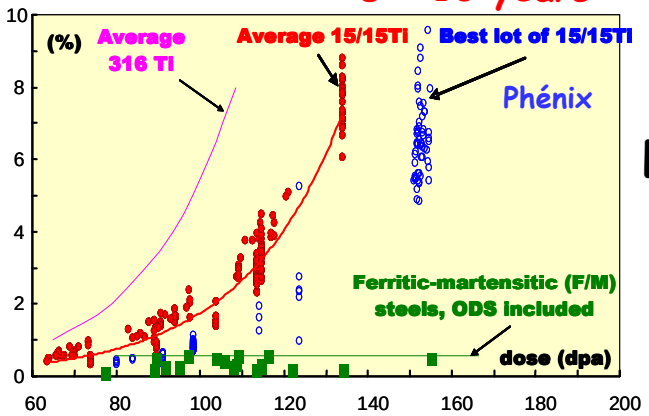
Dose	> 150 dpa
Stress	100 MPa
Temperatures	400 – 650°C

Low deformation





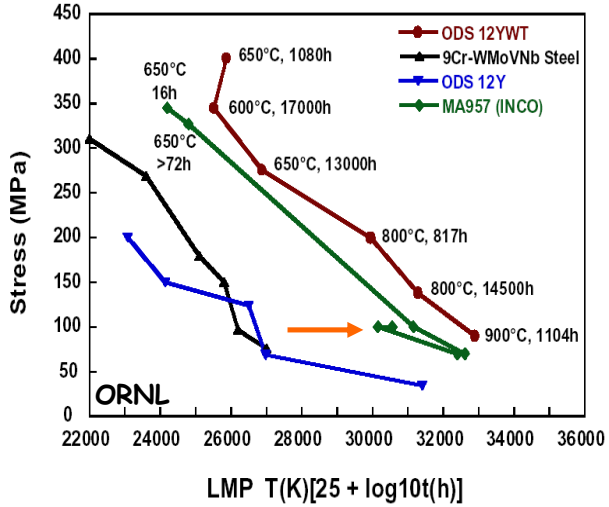
8 – 10 years

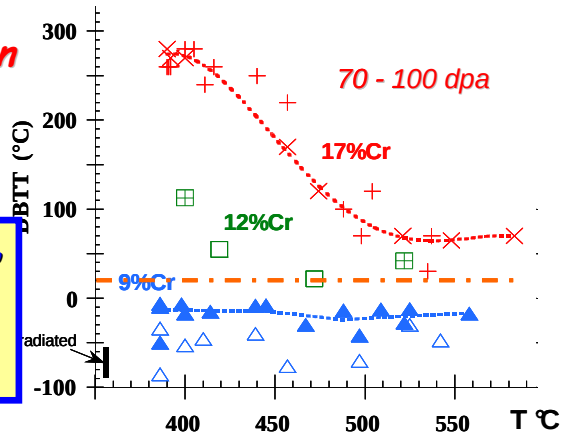


Key "technological" issues

- *Swelling*, Irradiation Creep
- *Embrittlement under irradiation*
- *Thermal creep, Mechanical prop.*
- *toughness, DBTT,…*
- *Weldability*
- *Behaviour in Na environment*
- *Fuel Cladding Chemical interaction*
- *Reprocessing*
- Phase transformation
- *Elaboration, ….*

Ferritic steel 13 – 18% Cr
Martensitic steel 9% Cr
ODS nano-structured





French program on ODS alloys for SFR application

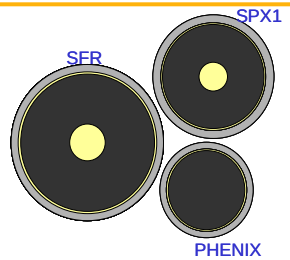
Dose	> 150 dpa
Stress	100 MPa
Temperatures	400 – 650°C

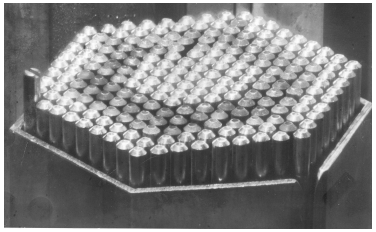
8 – 10 years

Low deformation

Phénix - Supernova, Matrix 1, 2
High doses Irradiations
BN600, Monju,…

Charged particles, JANNUS, HVEM…
Microstructure, α'Précipitation, …





Welding "without" fusion
FSW, UDW, SPS
PRW
Clad - Plug

Key "technological" issues

Swelling, Irradiation Creep
Embrittlement under irradiation
Thermal creep, Mechanical prop.
toughness, DBTT,…

Weldability
Behaviour in Na environment
Fuel Cladding Chemical interaction
Reprocessing
Phase transformation
Elaboration, ….

Specific device in Na
Investigations in Reactors

characterizations
Thermal ageing

Phenix
ferritic steels
1st ODS generation

Modelling

Test in nitric acid
Virgin steel
irradiated samples

Ferritic steel 13 – 18% Cr
Martensitic steel 9% Cr
ODS nano-structured

Elaboration tubes
Improvement in Fabrication route
New reinforced alloys

ODS steels

CEA-EDF-AREVA program

- "New" ODS steels developped by CEA

nano oxides - homogeneous

- Fe 9Cr 1W 0,3Mn 0,3 Si 0,2 Ni Ti Y_2O_3 *fine grains*
- Fe 9Cr 2W 0,3Mn 0,3 Si 0,2 Ni Ti Y_2O_3

martensitic

- Isotropic
- Easier to manufacture
- T < 750°C
- Corrosion resistance Fuel, HNO_3 ?

Reprocessing

- Fe 14Cr 1W 0,3Mn 0,3 Si 0,2 Ni Ti Y_2O_3
- Fe 18Cr 1W 0,3Mn 0,3 Si 0,2 Ni Ti Y_2O_3
- Fe 14Cr 2W Ti Y_2O_3

ferritic

- Anisotropic
- Possible embrittlement under irradiation
- Difficult to manufacture – recrystallization difficult to control
- Better behavior expected concerning:
  - the fuel cladding chemical interaction
  - the reprocessing of the fuel

SFR R&D program on ODS steels

400 – 650°C
> 150 dpa

❑ Challenge for SFR fuel cladding pins

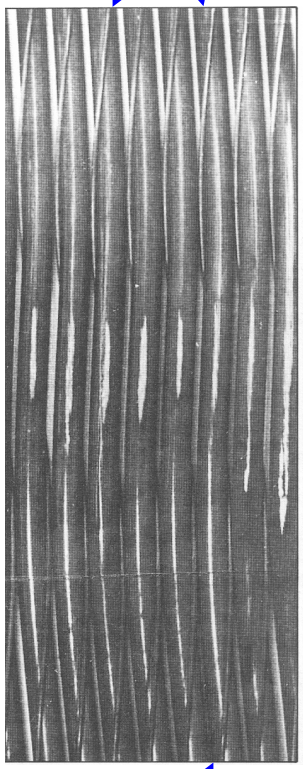
Low deformation under irradiation at high doses

➔ ODS steels Ferritic or Martensitic

- **very fine & *homogeneously* nano oxides distribution to expect reaching the target creep & irradiation resistances**
- **Mastering the industrial fabrication route of tubes**
  - *Weldability, Thermal creep, mechanical properties anisotropy*
- **Controlling the microstructural evolutions and the degradation of main using post irradiation properties**
  - *Swelling, Irradiation creep*
  - *ductility, toughness, Embrittlement, DBTT, …*
  - *Fuel Cladding Chemical Interaction*
- **Reprocessing**
  - *Behavior in Nitric acid*

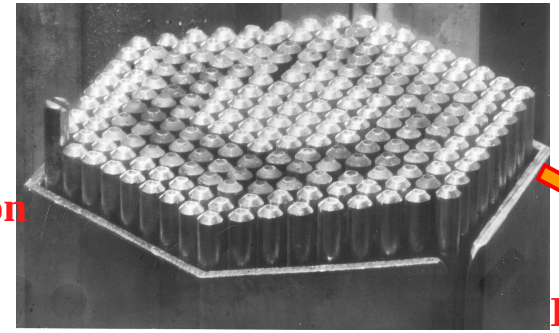
Fuel Subassembly
Sodium Fast Reactor

Fuel pin claddings

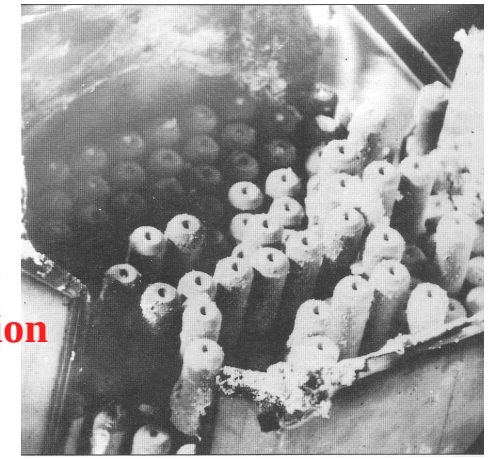


spacer wire

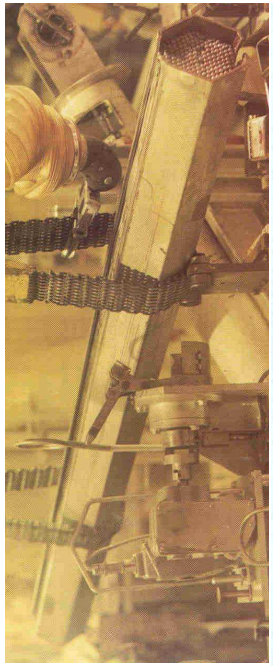
Irradiation

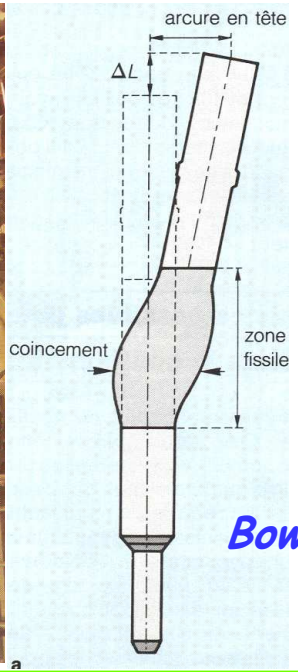


Irradiation



Large deformation of clads and wrappers



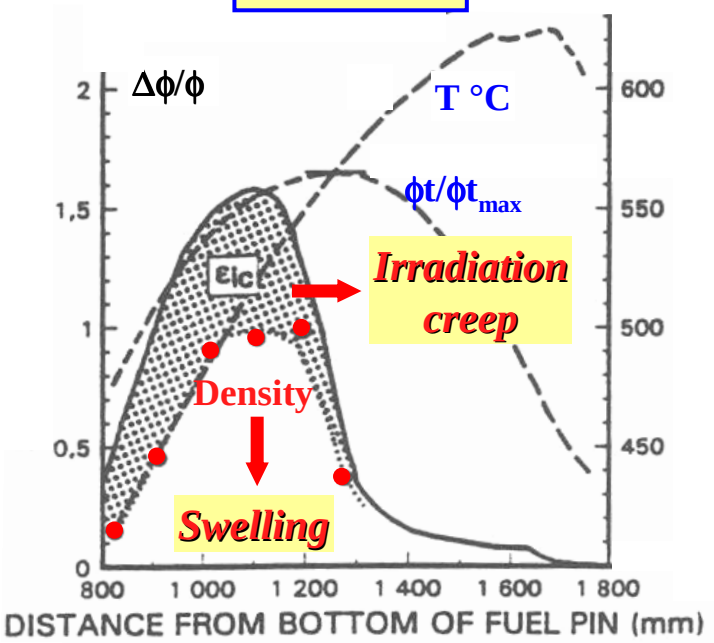


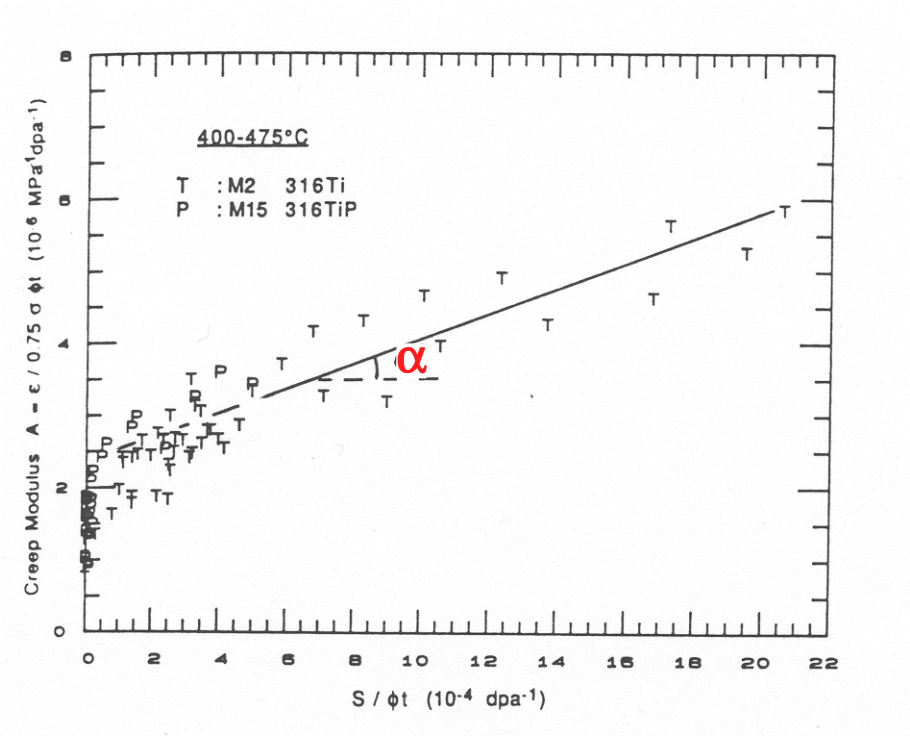
Bowing

Irradiation creep - Swelling

Clad

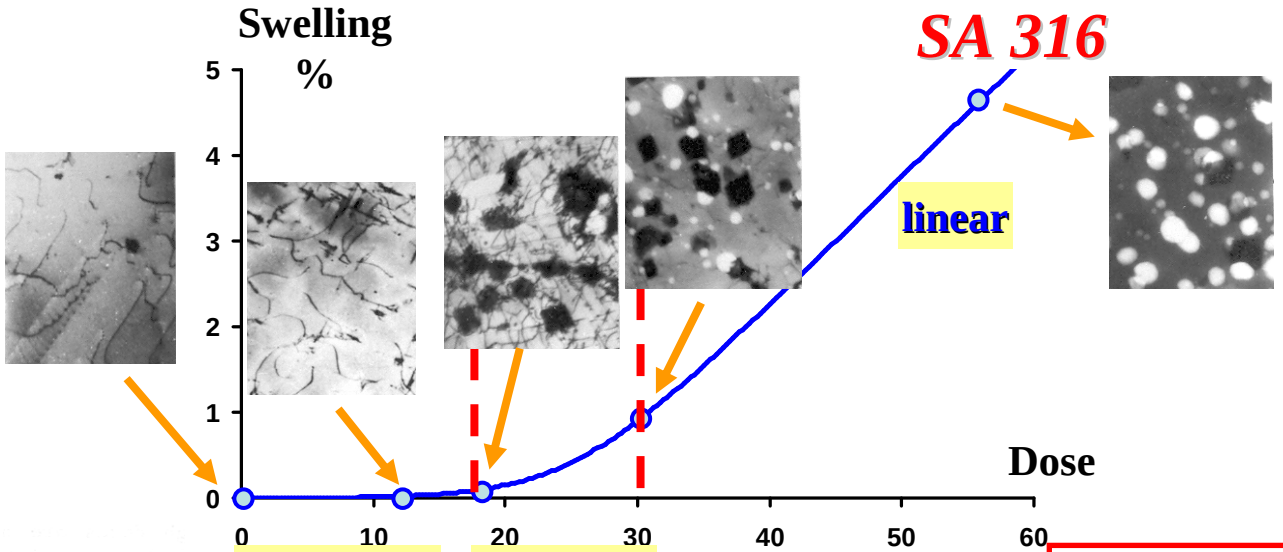
CW 316 Ti

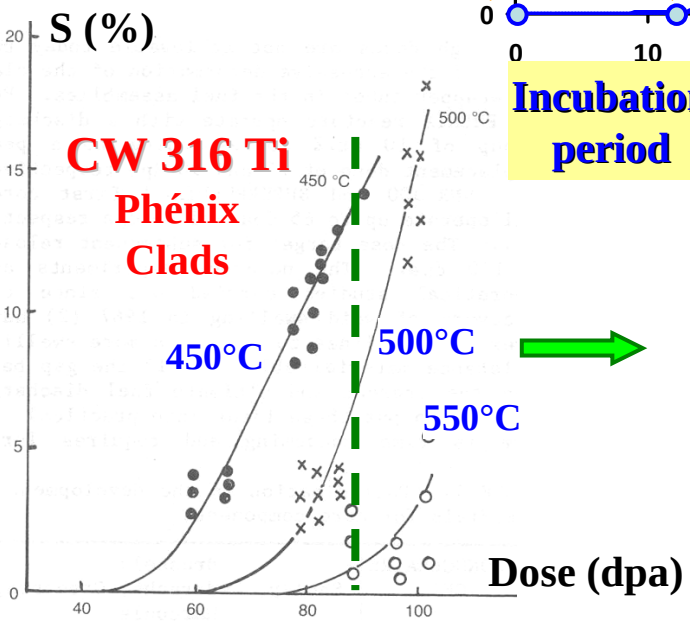


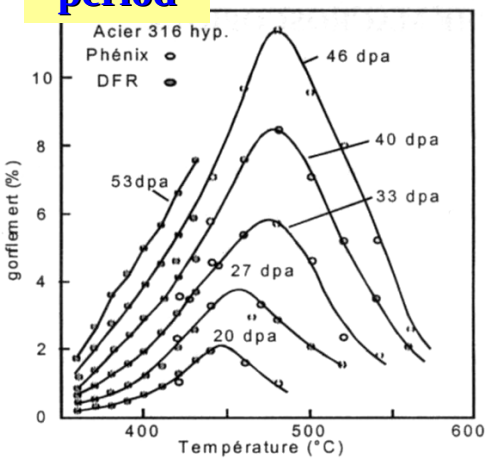


$$\dot{\varepsilon} / \sigma = B_0 + \alpha S / \phi t$$

Austenitic steels - Swelling







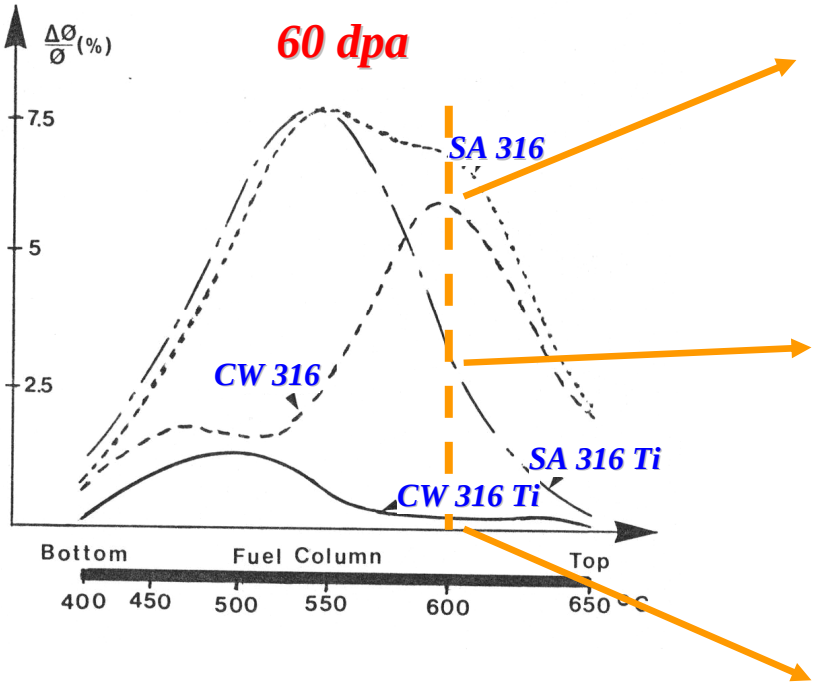
threshold phenomen

Temperature
Swelling peak

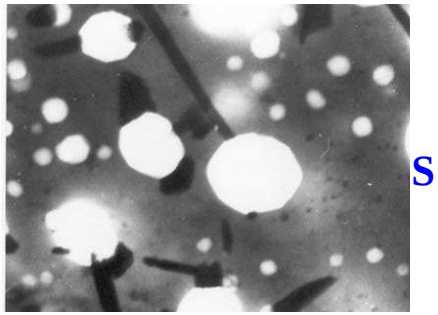
Void Formation
nucleation - growth

Incubation dose DI
Swelling rate $\dot{S}$

Swelling
Metallurgical state – Chemical composition

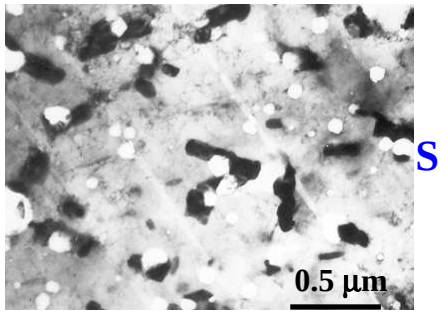


Microstructural instability
precipitation Ni, Si

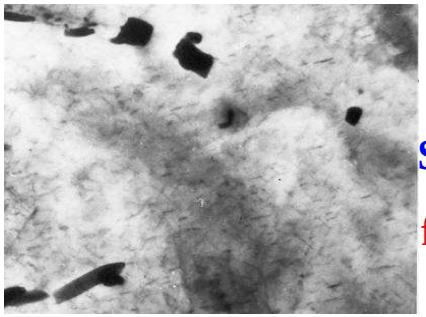


S = 10%

M_6C / voids



S = 2%

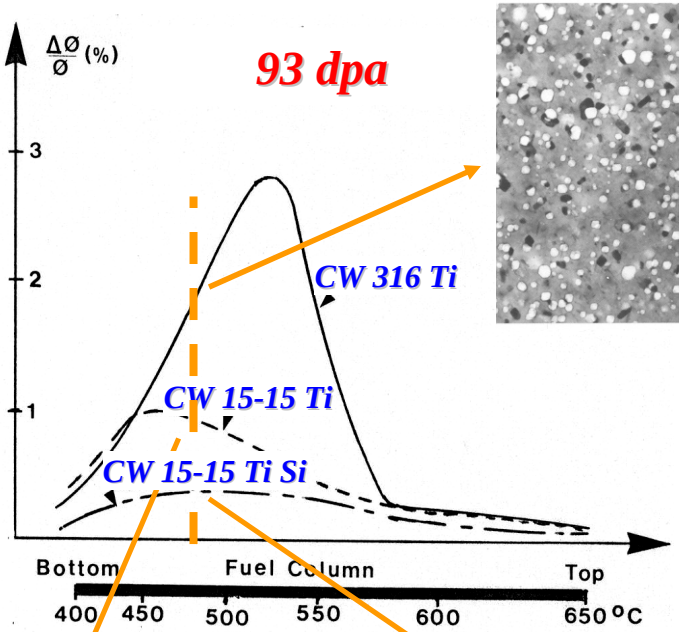


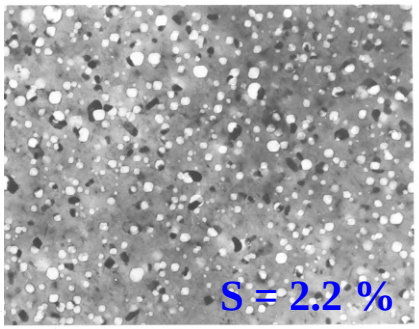
S = 0%

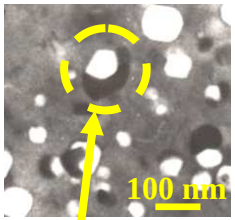
fine TiC / dislocations

SA 316 < SA 316 Ti < CW 316 < CW 316 Ti

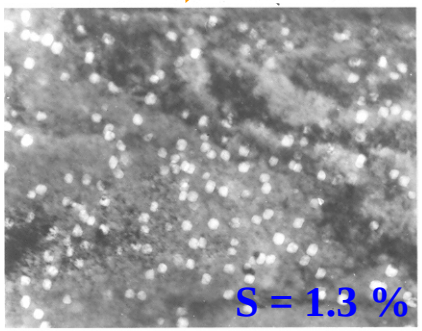
Swelling
Chemical composition

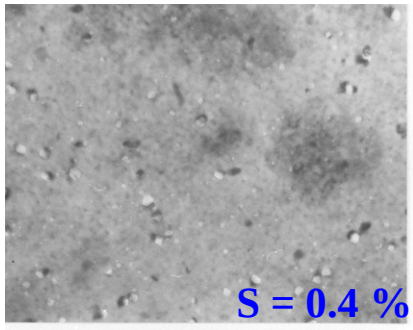






G phase / voids

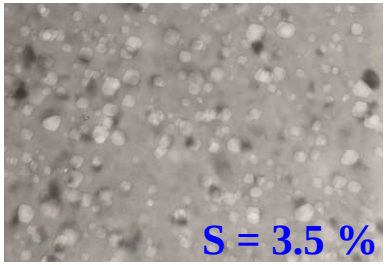




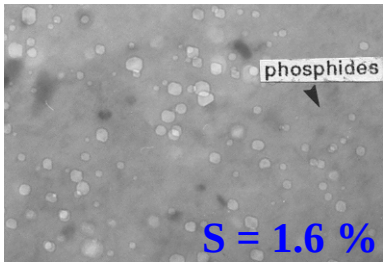
γ'
fine and uniform
precipitation

450°C – 80 dpa

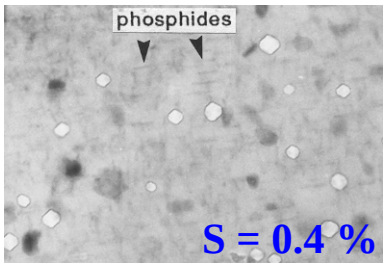
CW 316 Ti



P 230 ppm



P 900 ppm

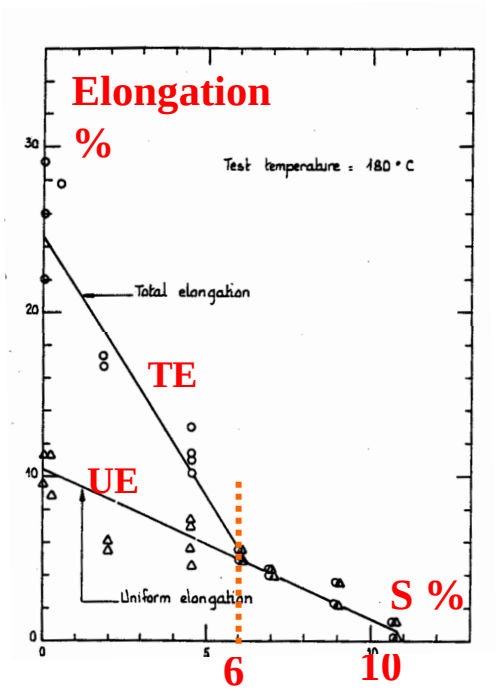


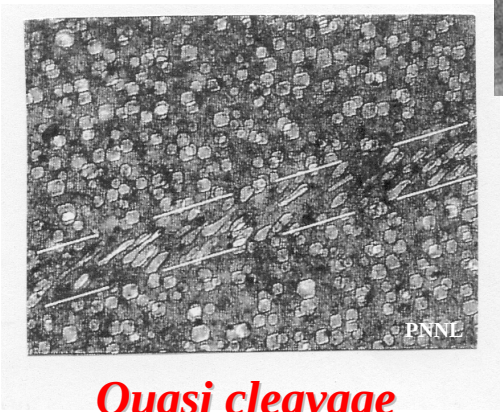
P 1550 ppm

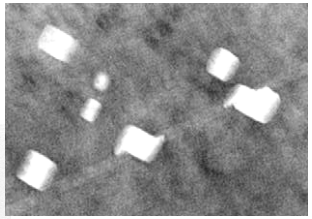
fine and uniform
precipitation of phosphides

Effect of Swelling on Mechanical Properties

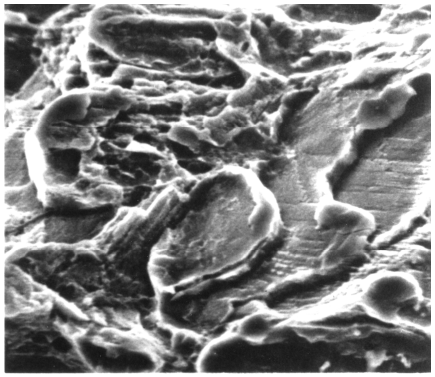
High swelling values

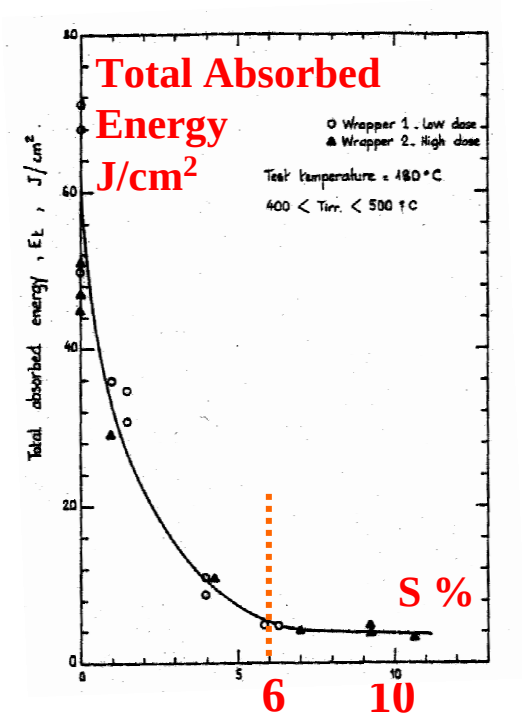






Quasi cleavage
Channel Fracture





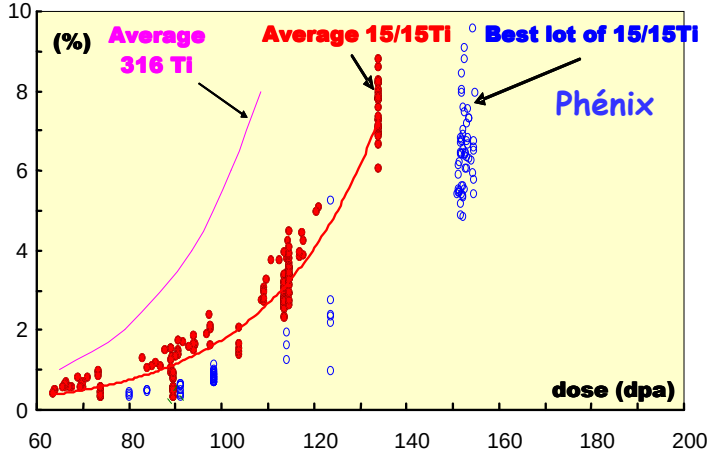
6% : Total elongation = Uniform elongation

10% : Elongation = 0

Impact properties/Toughness decreases with swelling
Limit 6%

Swelling of advanced austenitic steels

Clads



Improvment of swelling resistance
CW 316 ➔ W 316 Ti ➔ CW 15-15 Ti

⬇

CW 15-15 Ti Si

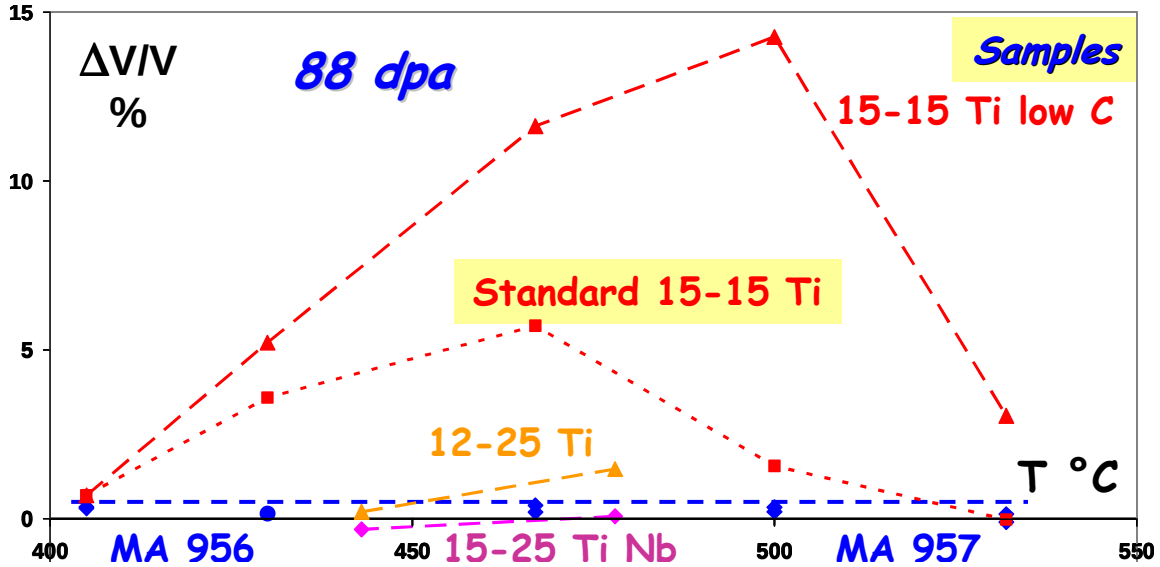
SUPERNOVA

Large swelling of
CW 15-15 Ti low C

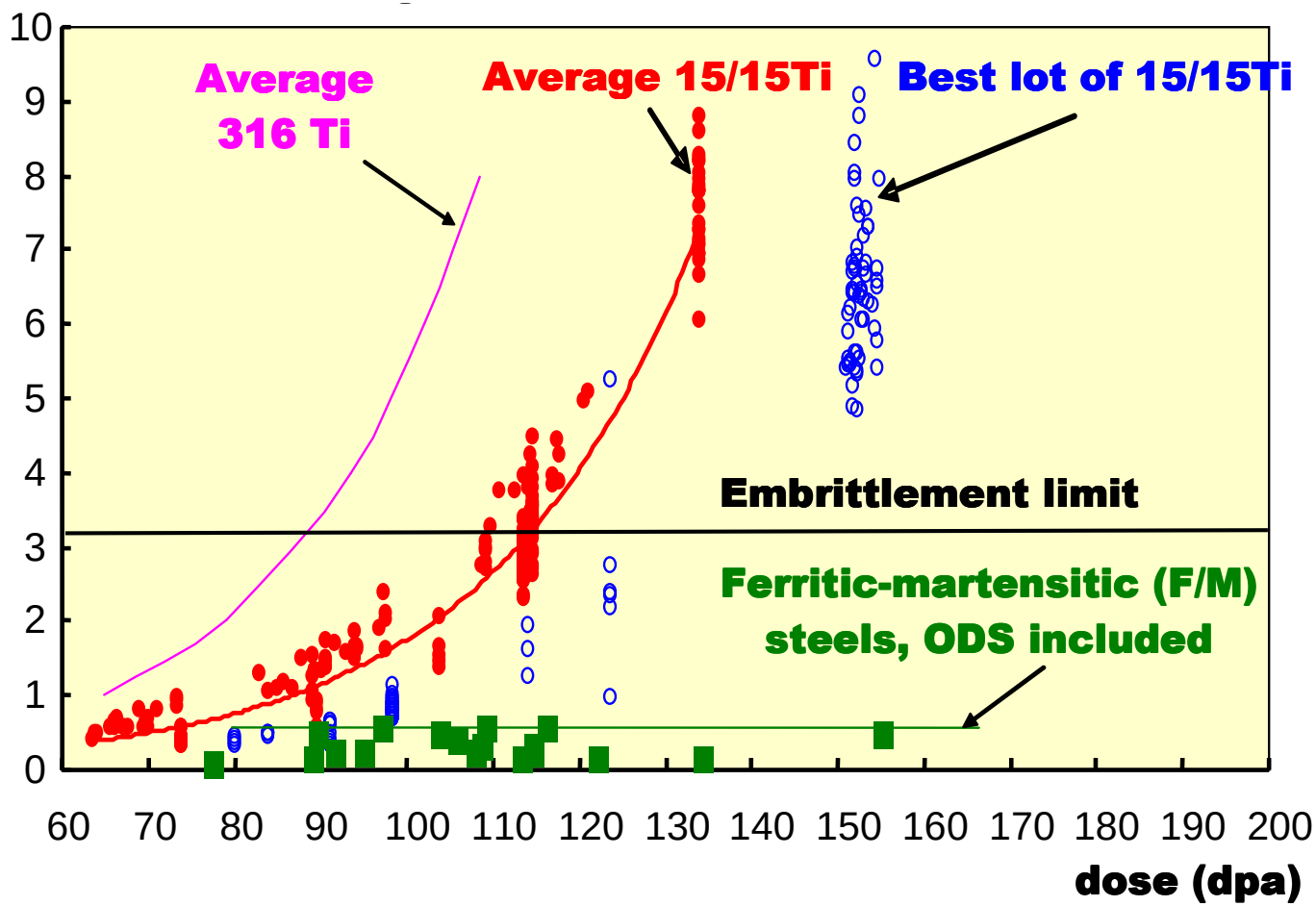
Improvment of swelling resistance
with 12Cr – 25Ni

Very good swelling resistance
of 15-25 TiNb

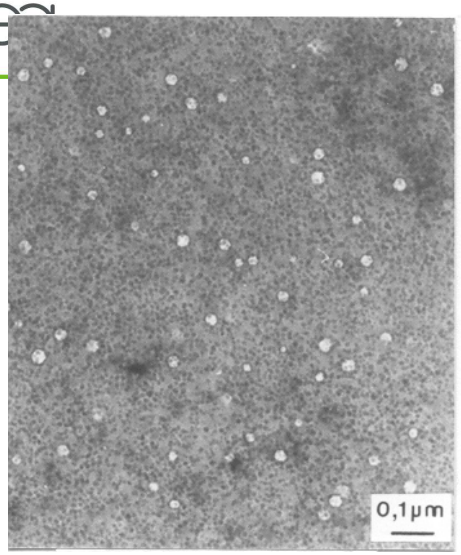
Equivalent to ODS steel – No swelling



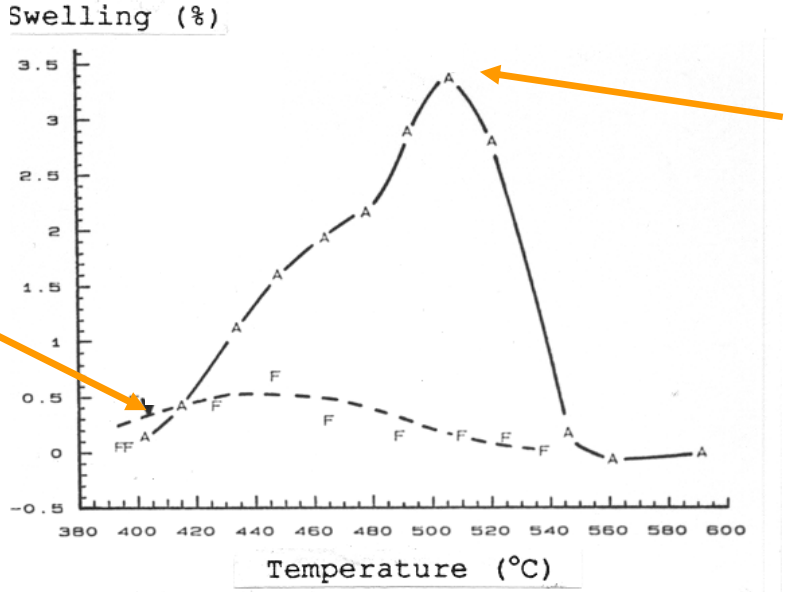
Ferritic – Martensitic steels - Swelling

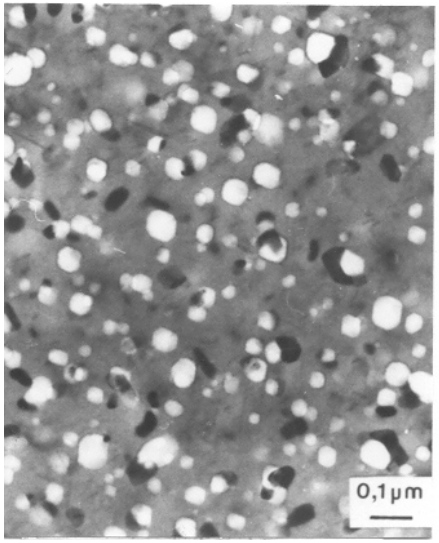


Ferritic – Martensitic steels - Swelling

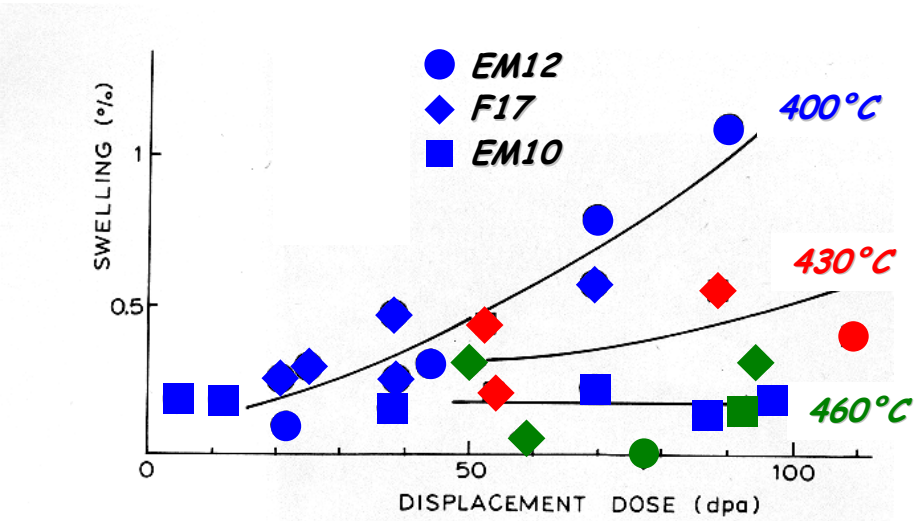


ferritic steel
F17





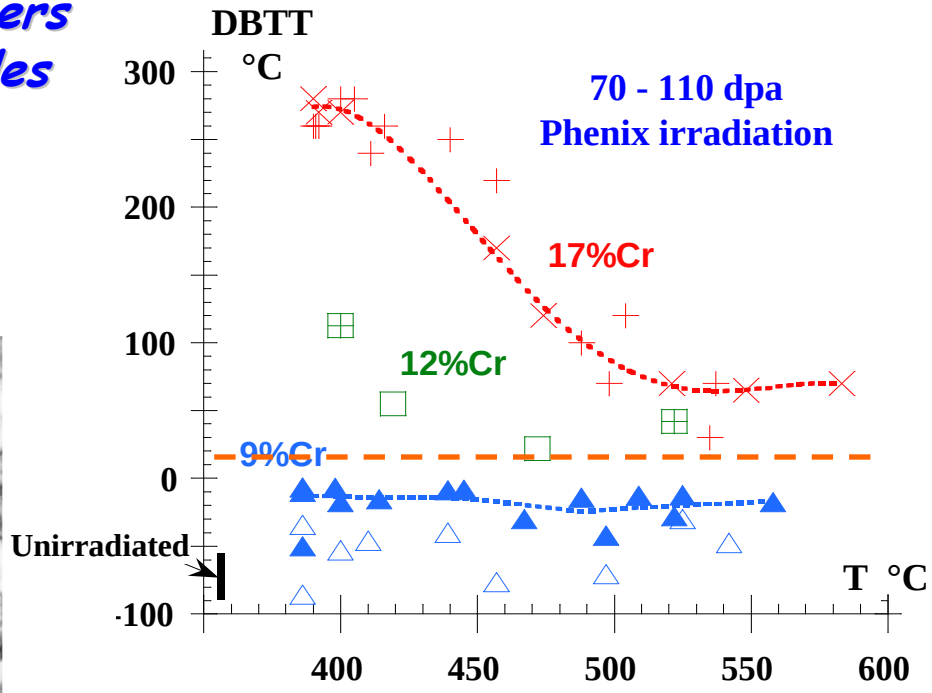
austenitic steel
316 Ti

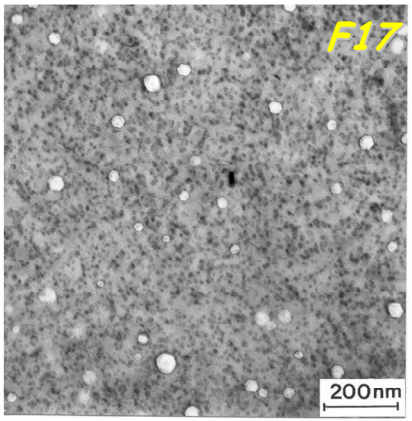


Swelling at low temperature
Max < 400°C
EM10 < EM12 ≈ F17

Ferritic – Martensitic steels - Embritlement

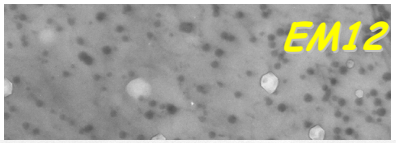
Wrappers Samples



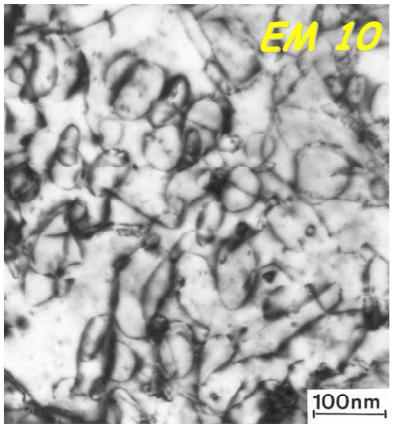


α'

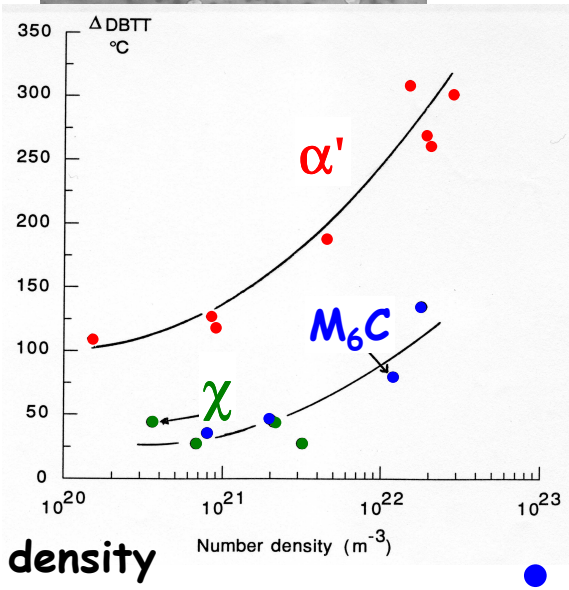
419°C 103 dpa



loops



400°C 70 dpa



Embrittlement increase with %Cr

EM 10
Reference steel for Phénix wrapper

martensitic 9Cr steel

Embrittlement
due to
dislocation loops + fine precipitation
correlated with number density

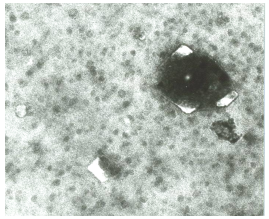
ODS steels - DY

fuel pin cladding
Experimental rig
Phénix

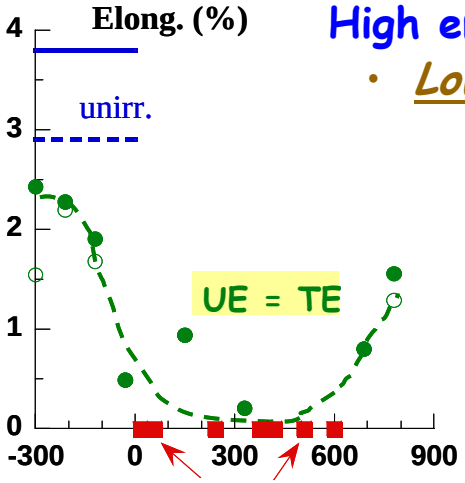
- **Swelling**
  - No diametral deformation
  - Only few voids observed at low temperature

Fe 13Cr 2Ti 1.5Mo 0.5Y_2O_3 TiO_2
first generation

81 dpa
400 - 580°C



- **Mechanical properties**



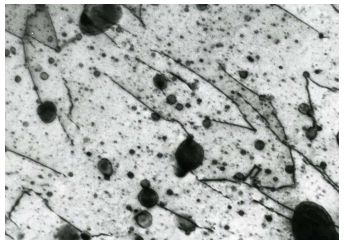
Rupture
Ductile "Cleavage"Ductile

High embrittlement induced by irradiation

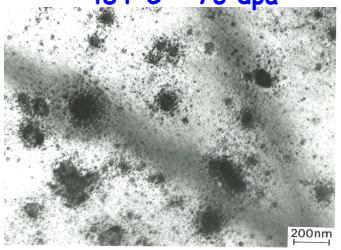
- *Low temperature* < 500°C

  α', loops and dissolution of oxides

Before irradiation

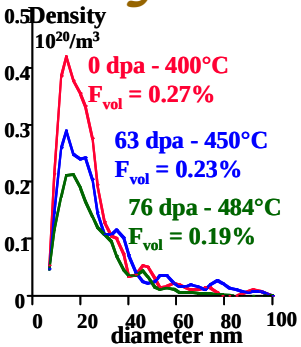


484°C - 76 dpa



halo of fine oxides around the biggest oxides

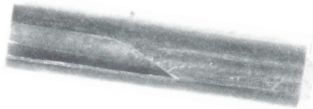
Hardening



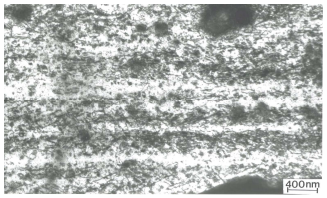
Denuded loop bands ⟹ *localization of the deformation*

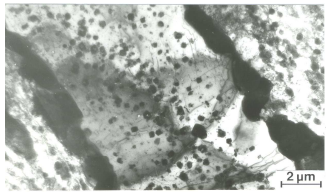
⟹ *Channel fracture*

// tube axis ⟹ *Rupture // tube axis*



During mechanical cutting
longitudinal rupture
Parallel to clad axis





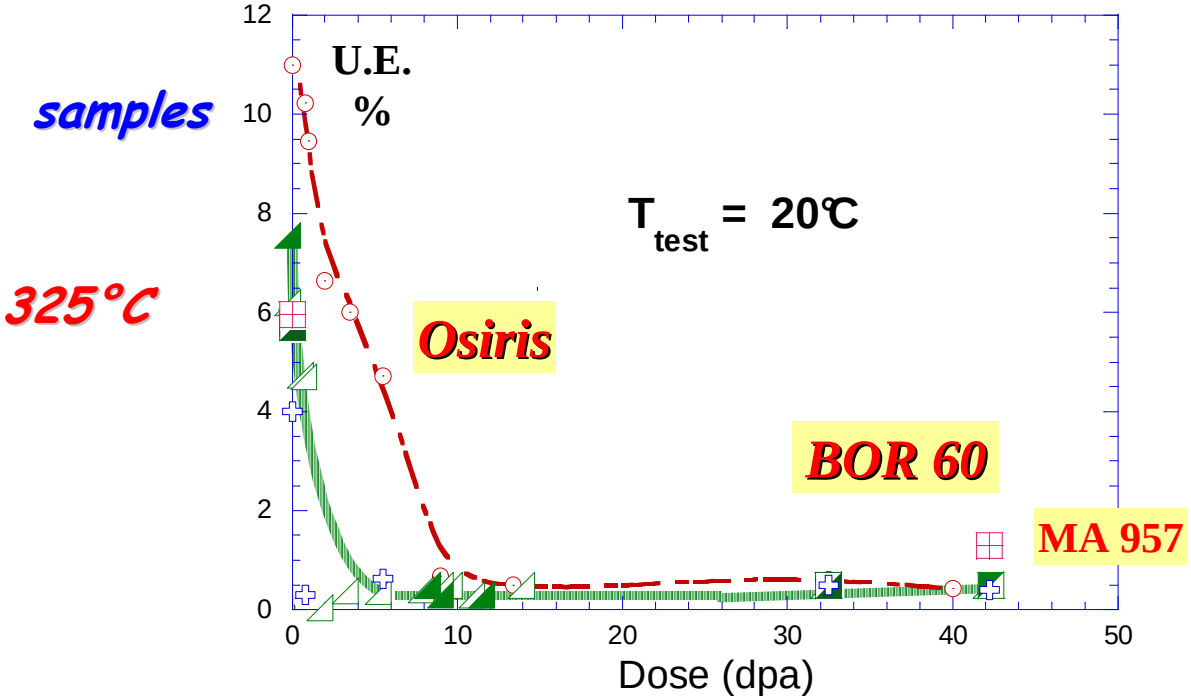
- *High temperature* > 500°C ⟹ *Dimples*

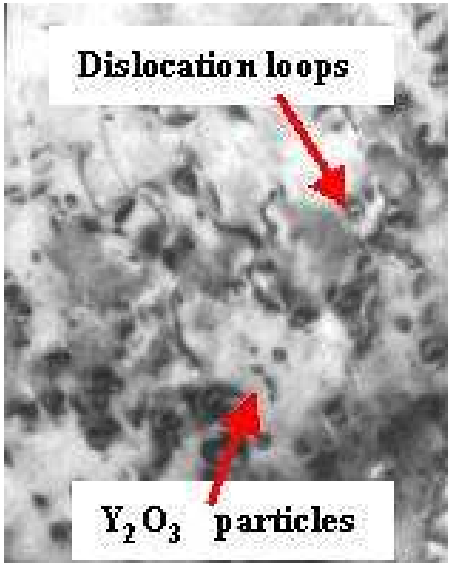
  high density of χ phases — *ductile rupture with dimples*

ODS steels

❑ Mechanical properties of irradiated MA 957 steel

Fe 14Cr 1Ti 0.3Mo 0.25Y_2O_3





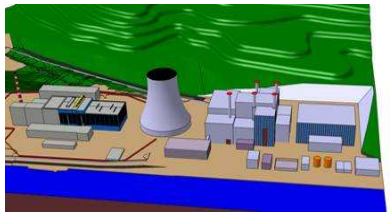
- ***ductility after irradiation even at 42 dpa***
  in spite of α' precipitation
- ***Stability of oxides distribution (up to 5 dpa)***

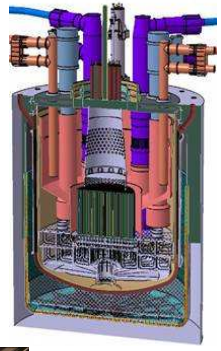
Organization of the French SFR R&D Program

- Generic R&D program in cooperation with AREVA and EDF
  - An attractive core with enhanced safety
  - Improved resistance to severe accidents
  - Energy conversion systems to minimize sodium risks
  - Simplified and optimized plant and system design
    - *Economy, operability, ISI & R*

Materials

- ASTRID development





Innovation Scoping studies

⇨ Technological studies
⇨ Choice of ASTRID power

Conceptual design end

Building Decision

Basic design end

Fuel Loading

2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Restart SFR Program

ASTRID

Back-end of fuel cycle & waste management

Materials

Evaluate different solutions

Feasibility Report on minor actinides partitioning

Position Report on minor actinides partitioning and transmutation

Start-up of core manufacturing workshop (AFC)

Start-up of MAs bearing fuels fabrication facility (ALFA)

Fuel fabrication facilities