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Structural Materials for Russian Fast Reactors Cores. Status and Prospects

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Outline

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Martensitic stainless steels

- Present status

Summary

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Introduction

The energy strategy of Russia in the period up to 2020 contemplates a gradual introduction of a new nuclear energy technology based on the fast breeder reactors with the closed MOX fuel cycle.

Since 1980 in Russia at Beloyarsk NPP commercial fast breeder reactor BN-600 is in operation. Design lifetime BN-600 expires in April 2010. Works on lifetime extension up to 2025 are conducted, which include management of service life of power unit's equipment /systems and enhancement of its safety.

According to the plans the fourth power unit at Beloyarsk NPP with the fast breeder reactor BN-800 shall be put into operation in 2014. Under developments is a commercial sodium cooled fast breeder BN-1200 .

Currently, for the BN-type reactors as promising structural materials for a staged increase in the fuel burn-up under consideration are austenitic and martensitic steels including those produced by the powder metallurgy method (ODS steels).

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Structural approach

Chemical Composition of FBR Core Austenitic Steels

Material	Element Composition, % mass.											
	C	Si	Mn	Cr	Ni	Mo	Nb	Ti	V	B	P	Ce
EI847	0.04-0.06	<0.4	0.4-0.8	15.0-16.0	15.0-16.0	2.7-3.2	<0.9	-	-	-	<0.02	-
EP172	0.04-0.07	<0.6	0.5-0.9	15.0-16.5	14.5-16.0	2.5-3.0	0.35-0.90	-	-	0.003-0.008	<0.02	-
ChS68	0.05-0.08	0.3-0.6	1.3-2.0	15.5-17.0	14.0-15.5	1.9-2.5	-	0.2–0.5	0.1–0.3	0.002-0.005	<0.02	-
EK164	0.05-0.09	0.3-0.6	1.5-2.0	15.0-16.5	18.0-19.5	2.0-2.5	0.1-0.4	0.25-0.45	0.15 calcul.	0.001-0.005	0.010-0.030	0.15 calcul.

The steels EI847, EP172, ChS68 were subjected to rather representative irradiation and post irradiation investigations. Based on the results of investigations steel ChS68 was recommended as a standard cladding material for BN-600 reactor fuel rod.

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Structural approach

The structure factors affecting swelling:

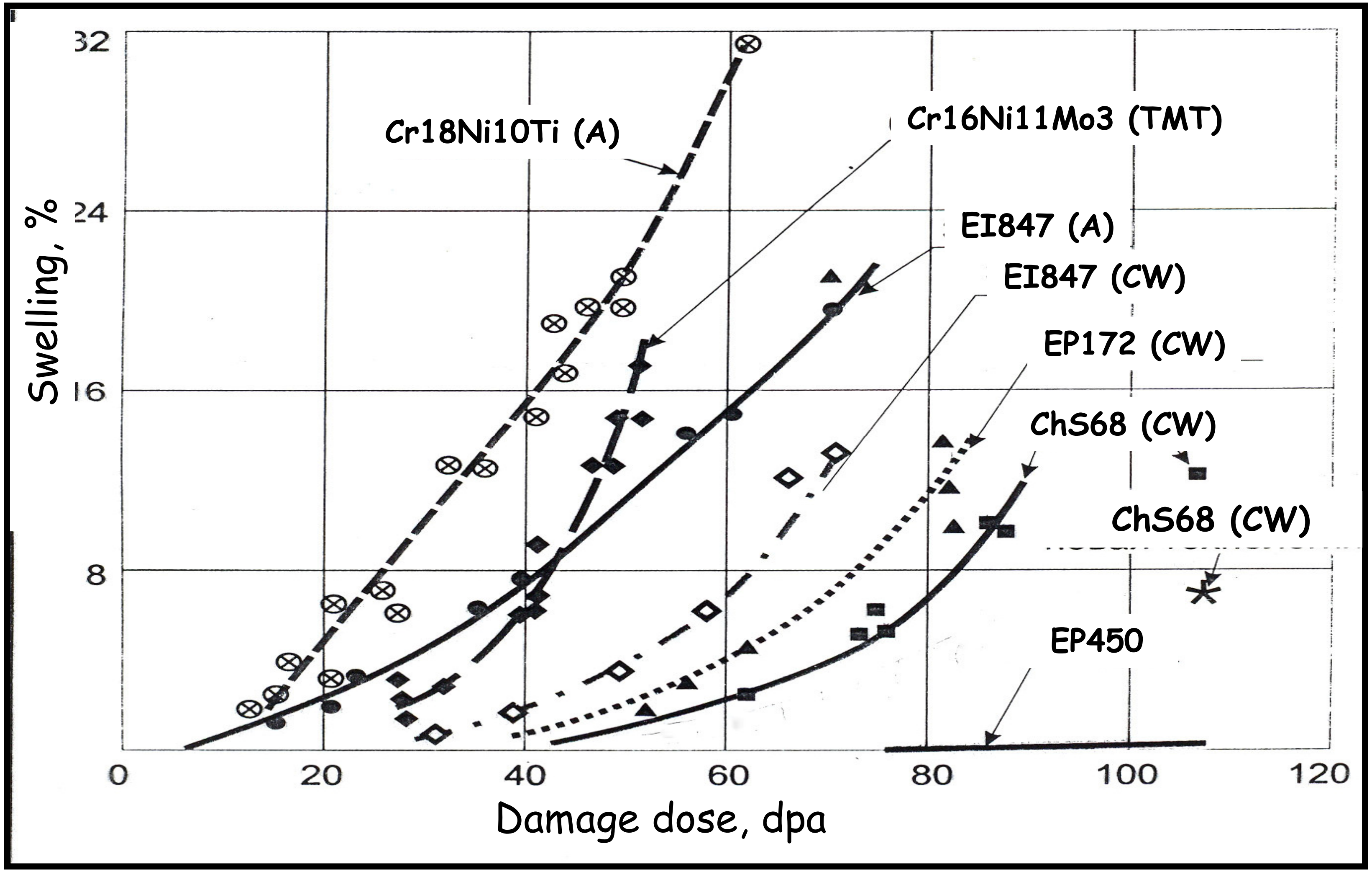
- A solid solution factor determined by a matrix solid solution concentration of alloying (primarily Ni) and impurity elements (C, Nb,Ti, B, Si etc.) that form "point defect-impurity" complex having changed diffusion characteristics;

- A phase instability factor that manifests itself as formation of precipitate particles, nature, composition, volume fraction, morphology and localization of which in many respects govern the process of void nucleation and growth;

- A dislocation factor when cold work increases density of point defect dislocation sinks and substantially delays the onset of an intensive void formation.

Structure factors that control swelling are specifically interrelated and influence one another.

Structural approach



Dose dependences of swelling for steels Cr18Ni10Ti(A), EI847(A), EI847 c.w., Cr16Ni11Mo3 (TMT), EP172 c.w., ChS68 c.w., EP450

Present status

The BN-600 reactor was put into operation at 1980 as the 3rd power unit of Beloyarsk NPP.

At present the following fuel SAs irradiated parameters are attained in BN-600 reactor with 01M2 core:

Maximum fuel burn up (Bmax) – 11.2%

Maximum damage dose (Dmax)– 82 dpa

SAs lifetime – 560 efpd

By 2014, it is planned to complete the construction of the 4th unit of Beloyarsk NPP with the BN-800 reactor.

Irradiation parameters the 1st core with MOX fuel:

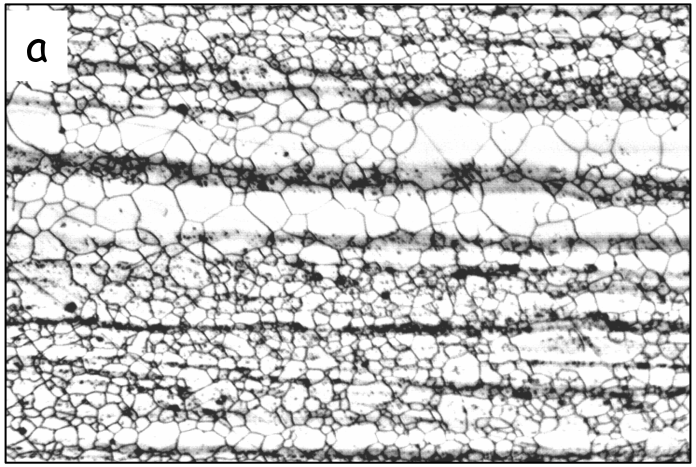
Maximum fuel burn up (Bmax) – 10%

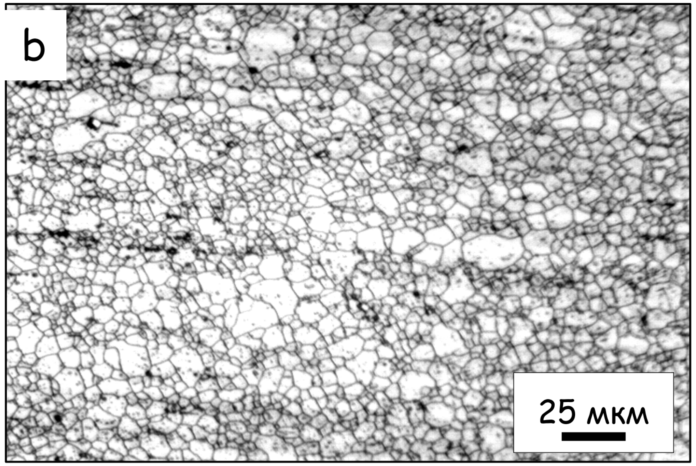
Maximum damage dose (Dmax) – 92 dpa

SAs lifetime – 465 efpd

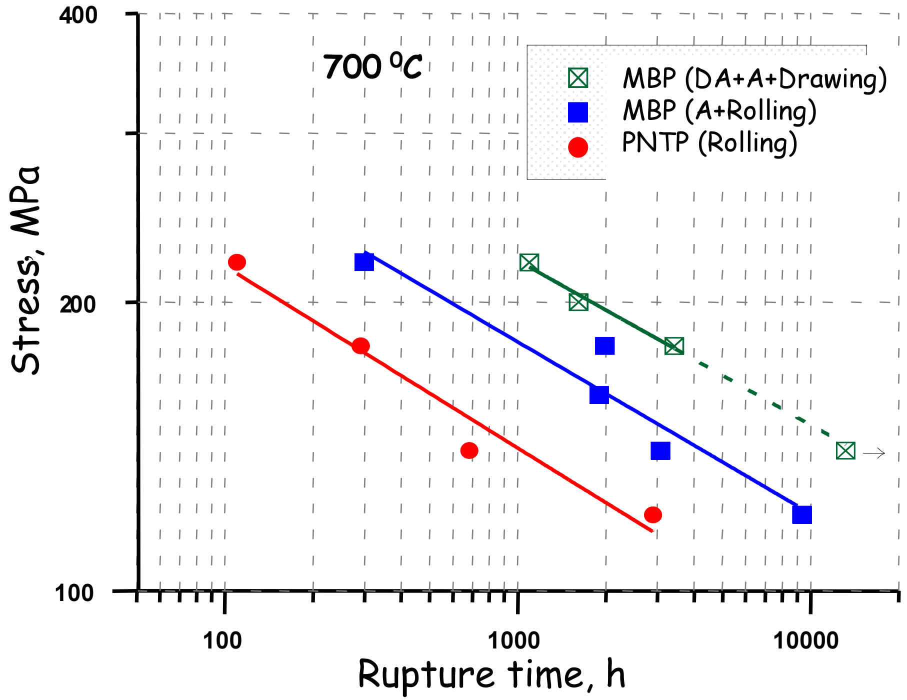
Cladding material in BN-600 reactor and in BN-800 1st core is austenitic steel ChS68 c.w.

Technology Improvement





Structure of ChS68 steel cladding tube:
a) after standard anneal 1060 ^{0}C;
b) using diffusion anneal 1180 ^{0}C



Creep rupture strength of ChS68

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Present status

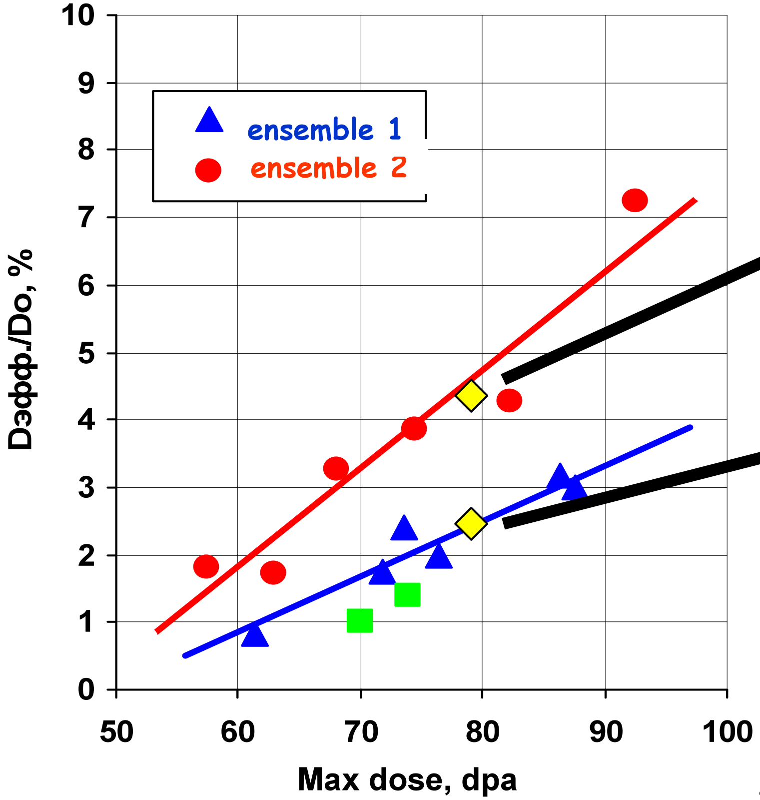
As an instrument for controlling and improving the quality of fuel claddings the methodology of irradiation and investigation of so-called reference fuel subassemblies (RSAs) is applied.

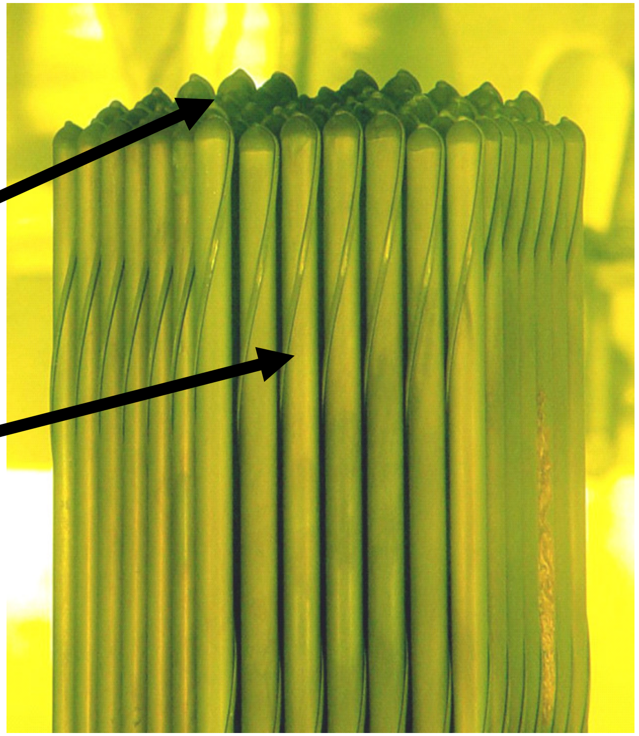
RSAs are set up with fuel claddings fabricated from ChS68 c.w. and meet the specified requirements.

Cartograms are compiled for RSAs that indicate the position of all claddings with certified original parameters.

After shape changes of fuel claddings are determined and results are analyzed conclusions on conditions of fuels and fuel assembly as a whole are promptly issued.

PIE results on BN-600 irradiated FAs





Diameter change
of ChS68 fuel pin

The design SSC estimates of ChS68 steel claddings of the reference FA fuel rods allow the forecast that the fuel rod serviceability will be ensured up to the dose of ~ 92 dpa.

Present status of austenitic steels

Steel ChS68

OBJECTIVE

Optimization of composition and structure of ChS68 steel claddings for validation of their serviceability up to ~ 92 dpa

IRRADIATION CONDITIONS

4 RSAs

start of irradiation: May 2008

maximal dose: 82 dpa

87 dpa

3 RSAs (Si=0,5-0,8%)

maximal dose: 82 dpa

87 dpa

Present status of austenitic steels

Steel EK164

OBJECTIVE

validate serviceability of EK164 steel claddings up to ~ 110 dpa

IRRADIATION CONDITIONS

2 ESAs "COMBI" (EK164 and ChS68)
start of irradiation: May 2006
end of irradiation: May 2008
maximal dose: 77 dpa

6 ESAs
start of irradiation: May 2008
November 2008
maximal dose: 82 dpa
105 dpa

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Martensitic steels

Chemical Composition of FBR Core Martensitic Steels

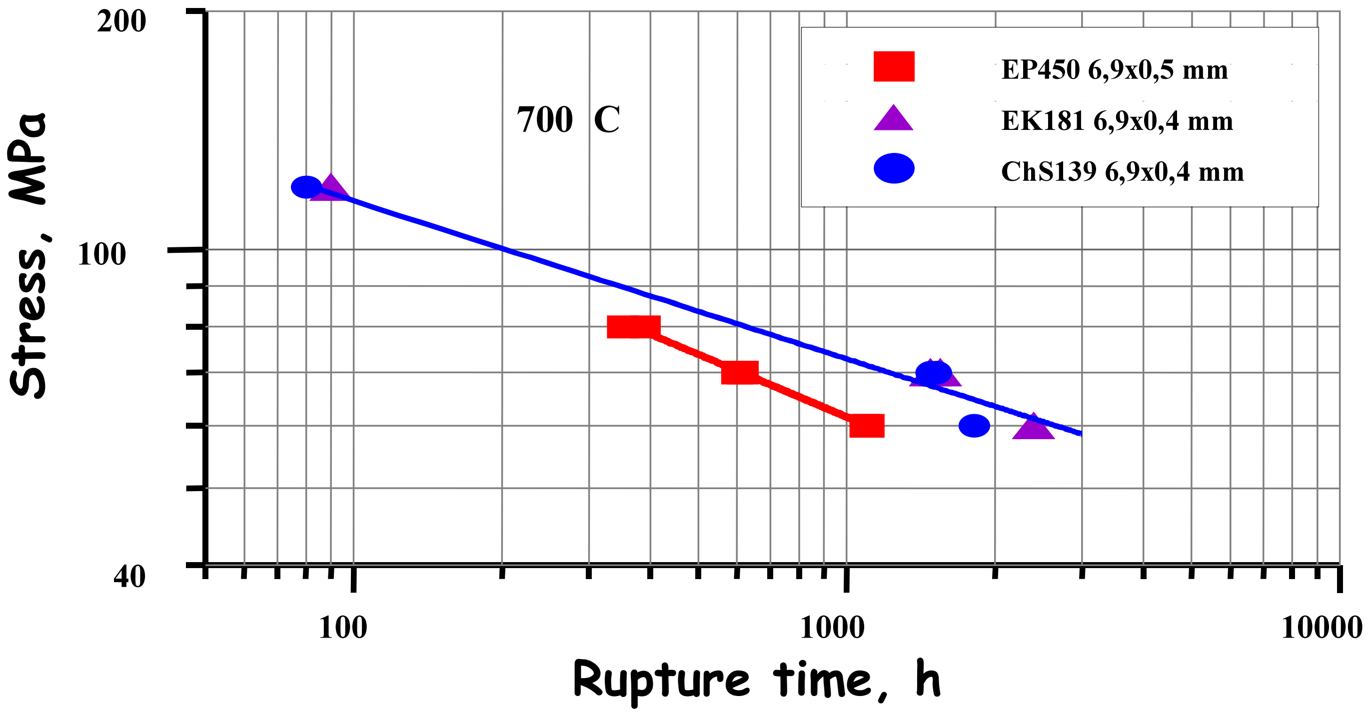
Material	Element Composition, % mass.											
	C	Si	Mn	Cr	Ni	Mo	Nb	V	B	W	Ti	Ta
EP450	0.10-0.15	<0.6	<0.6	12.0-14.0	<0.3	1.2-2.8	0.25-0.55	0.1-0.3	0.004	-	-	-
EK181	0.10-0.20	0.3-0.5	0.5-0.8	10.0-12.0	<0.1	<0.01	<0.01	0.2-1.0	0.003-0.006	1.0-2.0	0.03-0.3	0.05-0.2
ChS139	0.18-0.20	0.2-0.3	0.5-0.8	11.0-12.5	0.5-0.8	0.4-0.6	0.2-0.3	0.2–0.3	0.003-0.006	1.0-1.5	0.03-0.3	-

Early in 70ies 12% Cr steel EP450 was first suggested as a material for fast reactor FAs shrouds and fuel claddings.

In 1989 ferritic-martensitic steel EP450 was recommended for use as a standard material of FAs shrouds. The application of this steel as FAs shrouds and steel ChS68 c.w. as fuel claddings reliably ensured the failure-free operation of the BN-600 reactor at the burnup of 11.2% h.a. and damage dose of 82 dpa. There is every reason to assume that the EP450 steel shrouds of fuel assemblies shall not limit an increase in the burnup of fuel.

Steels for fuel claddings

Ferritic-martensitic 12 % Cr steels



Long-term strength of cladding tubes from steels EP450, EK181 and ChS139 upon biaxial tension by test temperature 700 °C

Time to rupture at 700c of EK181 and ChS139 fuel tubes is a factor of 1,5-2 longer than that of EP450 steel.

Steels for fuel claddings

Ferritic-martensitic 12 % Cr steels

The results of the investigations of BOR-60 irradiated ($T_{irr.}$=340^{0}C, damage dose 8 dpa) EK181 specimens evidence that the irradiated specimens retained the acceptable levels of impact strength and ductility.

The BOR-60 irradiation test and investigations of EK181 steel specimens are in progress.

To check up experimentally their usability it is planned beginning from 2010 to irradiate one EFA with clad fuels in the BOR-60 reactor and two MFAs with EK181 and ChS139 steel samples in the BN-600 reactor to the maximal damage dose of ~140 dpa.

Steels for fuel claddings

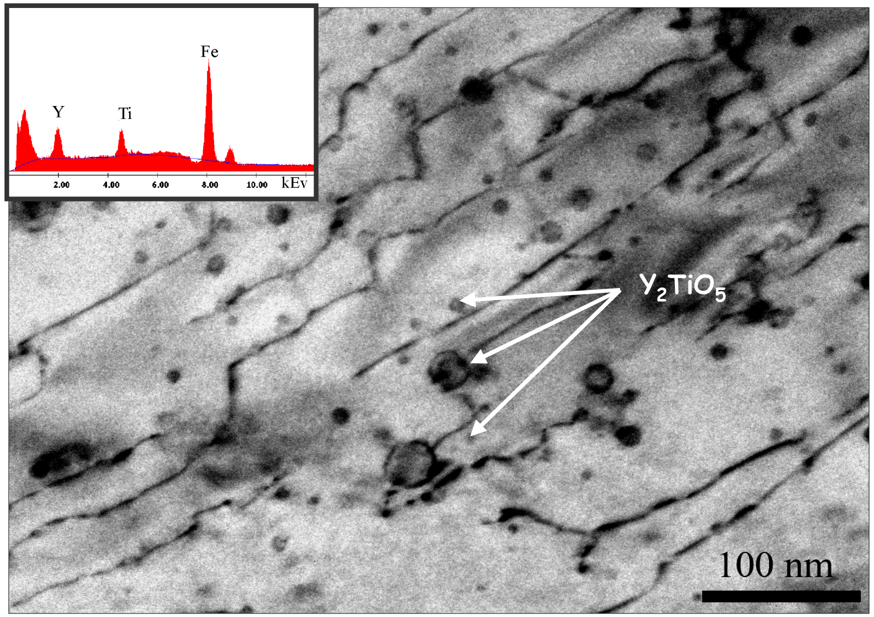
Ferritic-martensitic 12 % Cr steels

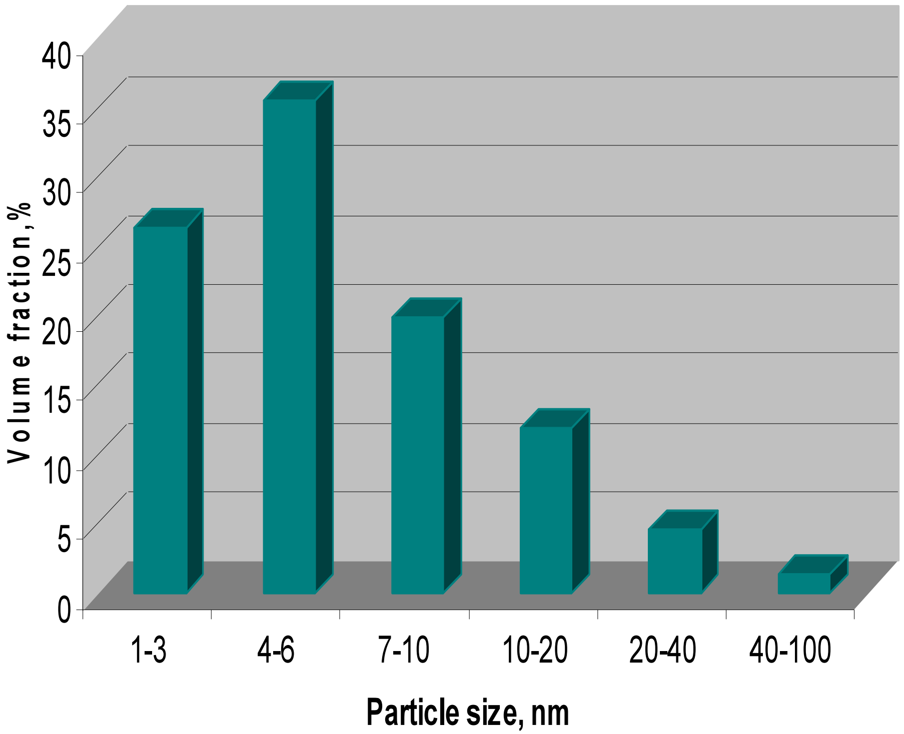
Steel	Test temperature, ^{o}C	Stress, MPa	Creep rate, %/h
EP450	650	140	$1,2*10^{-2}$
EP450 - ODS	650	140	$2,4*10^{-4}$
EP450	700	120	9,1
EP450 - ODS	700	120	$1,8*10^{-3}$

Results of thermal creep tests of plate specimens from EP450 and EP450-ODS steels

Steels for fuel claddings

Ferritic-martensitic 12 % Cr steels





Microstructure of the tubes from EP450-ODS steel and oxide sizes distribution

Summary - Austenitic steels

An increase of the fuel burn-up in BN reactors is restrained by the swelling of the austenitic Cr-Ni steel claddings of fuels at high damage doses. Currently in the BN-600 reactor experiments are in progress to validate the serviceability of the austenitic class steels used as claddings: ChS68 steel - up to ~ 92 dpa, EK164 steel - up to ~ 110 dpa.

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Summary-Martensitic steels

An increase of the serviceability of fast reactor fuel claddings to the doses of ~ 140 dpa is resolved via applying novel 12 % Cr martensitic steels of EK181 and ChS139 types.

To check up experimentally their usability it is planned beginning from 2010 to irradiate one EFA with clad fuels in the BOR-60 reactor and two MFAs with EK181 and ChS139 steel samples in the BN-600 reactor to the maximal damage dose of ~140 dpa.

Summary-ODS Ferritic-Martensitic steels

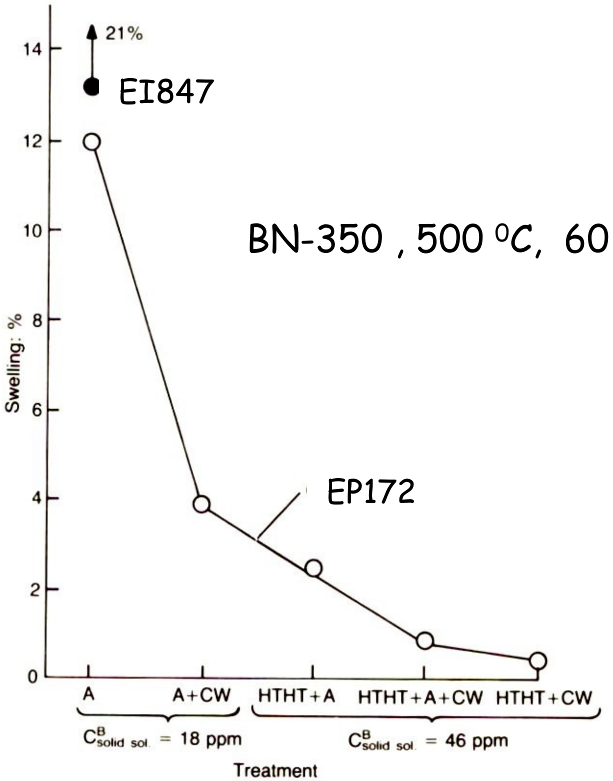
To ensure the serviceability of BN reactor fuel claddings up to damage doses of ~ 180 dpa the work has been commenced to design high-temperature strength chromium ODS steels.

The mastering of the fabrication process and complex out-of-reactor investigations of fuel rod tubing from ODS steels of ferritic (on the base EP450) and martensitic (on the base EK181) classes and their weldments are under way.

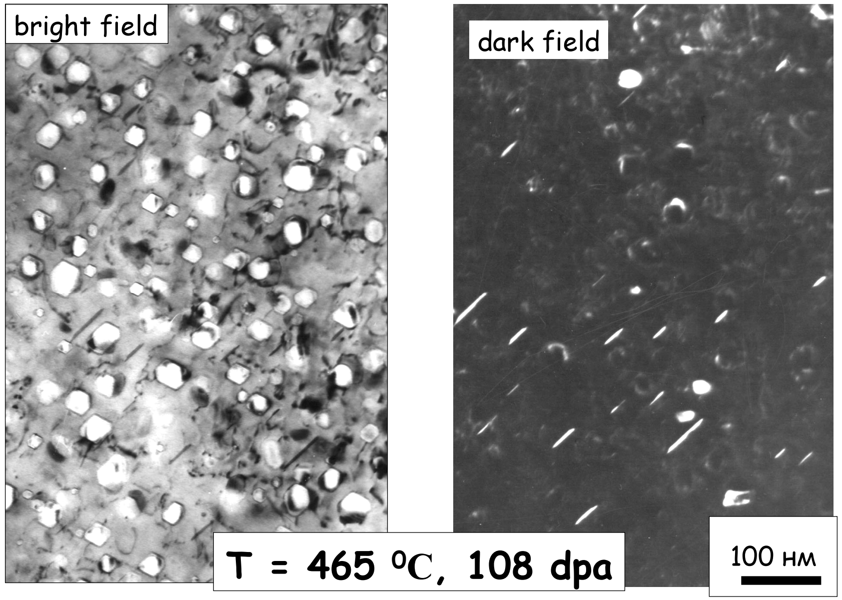
Preparations are in progress for in BN-600 reactor tests of this class of materials within two MFAs to the maximal damage dose of ~ 140 dpa.

Structural approach – solid solution factor

Influence of heat treatment and boron on swelling of EI847 and EP172 steels



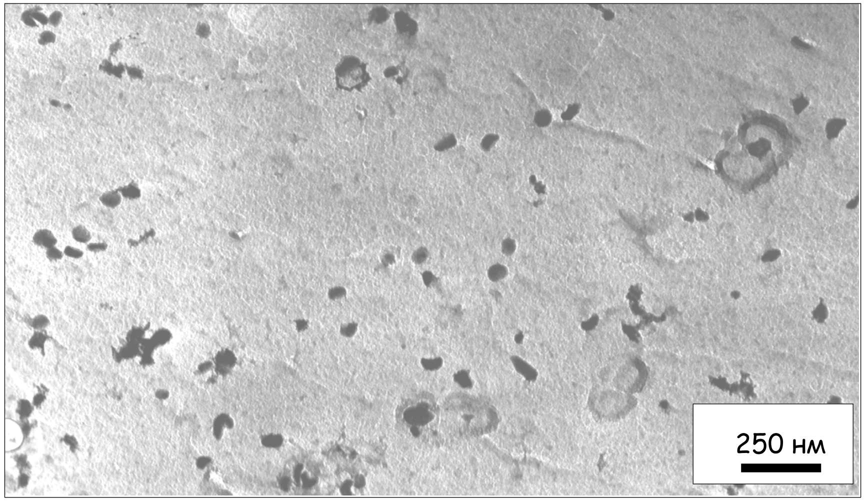
Microstructure of steel ChS68 C.W. irradiated in BN-600

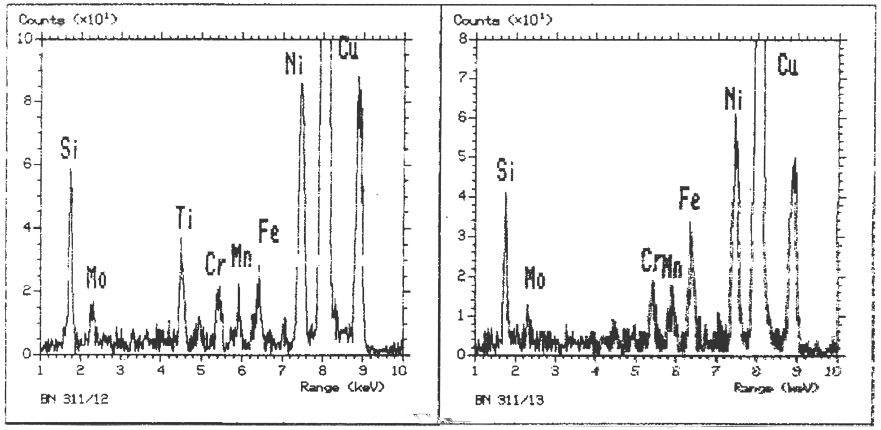


The important part of the technology that affects the resistance to swelling is austenization process

Structural approach – phase instability factor

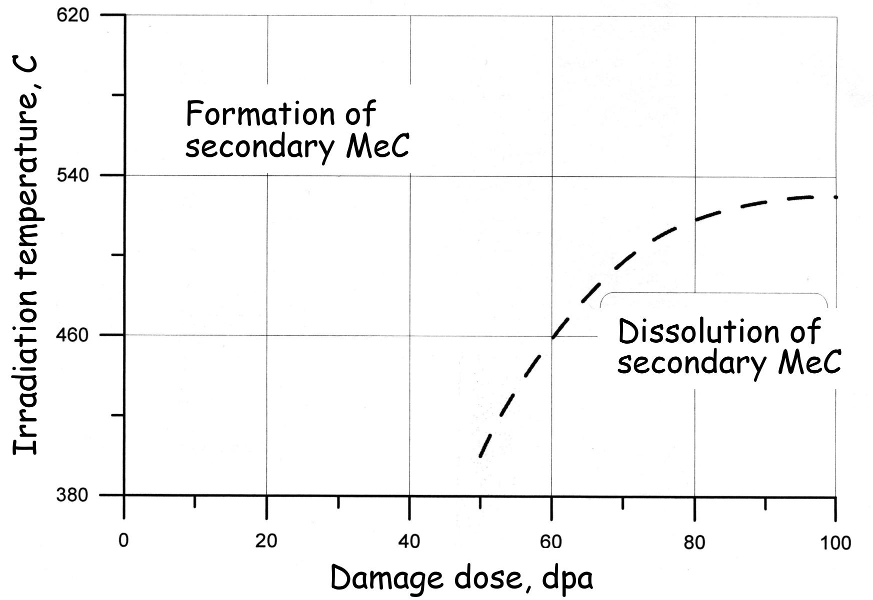
G-phase particles on extraction replica





X-ray spectrum of extracted G-phase particle

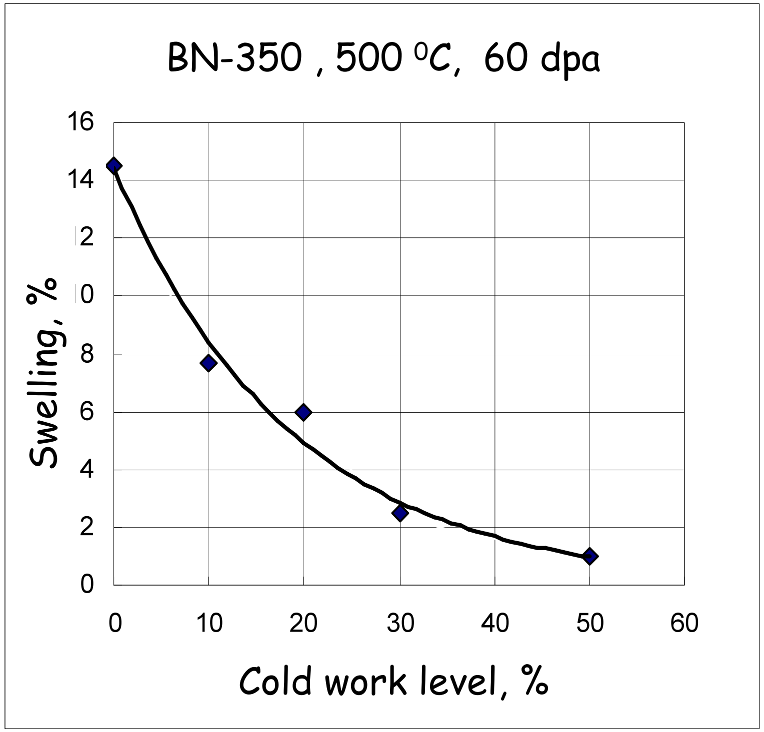
Scheme of the secondary carbides MeC behavior in irradiated austenitic stabilized steels



The interrelation has been established:
- the temperature ranges of the phase instability of secondary MeC carbides
- G phase formation
- the maximum of swelling.

Structural approach – dislocation factor

Effect of cold work level on EI847 swelling



Progress in c.w. level of austenitic steel

ε = 15 %

ε = 18 ±2 %

ε = 20 ±3 %

ε = 20-25 %

What is the limiting dose at which the favourable effect of C.W. increase disappears?