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«ROSATOM» STATE ATOMIC ENERGY CORPORATION

FUEL COMPANY TVEL

Development, manufacturing and installation for irradiation the experimental nuclear fuel rods of accident tolerant fuel into MIR reactor

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Accident Tolerant Fuel

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Goals and Objectives:

- to find, study and introduce alternative fuel systems and technologies that **increase safety** and providing fuel behavior under normal operating conditions and accident conditions as well as increase the **economic indicators** of existing nuclear reactors;
- **reduction of hydrogen** production or elimination of opportunities for its formation

Solution:

- coatings on a zirconium claddings
- heat-resistant alloys for claddings
- ceramic claddings (SiC)
- use of fuel with high thermal conductivity

Materials for cladding (General Requirements)

The cladding should have the following properties:

Production

- To be technological;
- To be sealed;
- To be monitored

Thermo-mechanical behavior

- High thermal conductivity;
- High temperature of melting;
- High strength;
- High ductility;
- Impermeability to gas fission products (at all stages of operation and storage)

Corrosion behaviour

- High corrosion resistance in the reactor;
- High corrosion resistance in the steam;
- Low level of hydrogen production;
- Absence of hydrogen brittleness

Materials for cladding (General Requirements)

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The cladding should have the following properties:

Chemical compatibility

- Compatibility with irradiated and non-irradiated fuel;
- Compatibility with reactor coolant;
- Compatibility with components of fuel assembly (chiefly in relation to formation of eutectics);

Behavior under irradiation

- Predictability of thermomechanical and corrosive behavior under irradiation;
- Resistance to fuel-cladding interaction;
- Dimensional stability.

Coating

- Low neutron loss (thickness <15 microns);
- The same mechanical properties of the cladding (with coating and without it);
- Increased wear resistance;
- Low level of oxidation and hydrogen production during an accident.

Cr Coatings

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Production

\+ The technology is developed;

It does not require a systemic change in the process

Operation

\+ High mechanical and corrosion properties;

Possible protection of fuel rods from debris damage and fretting

Accident conditions

\+ Low oxidation rate;

Eutectic formation at T = 1330°C — Problem task

42KhNM Alloy (42CrNiMo)

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Production

\+ The technology is developed;
It is used as a structural material for safety rod.

Operation

\+ High mechanical properties;

Problem tasks: High neutron absorption;
Transient modes.

Accident conditions

\+ Low oxidation rate;

Problem task: The melting temperature is lower than that of Zr alloys.

Ceramic Claddings (SiC)

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Problem tasks

Production

Technology;

Sealing

Operation

+ Decrease of the neutron absorption;

Problem tasks

Interaction with water (loss of material);

Low ductility;

Possible swelling

Accident conditions

+ High oxidation resistance in a steam;

Saving of geometry

Two-layer (multilayer) claddings (inner coating Mo, Nb, Ta, etc.)

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Production

Problem tasks

Complex production;

Sealing.

Operation

\+ Elimination of eutectic reactions;

Problem tasks

High neutron absorption.

Accident conditions

\+ Increased strength (including at temperatures > 1200˚C) and resistance to form change.

Fuel compositions

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\+ High density;
High thermal conductivity;
Compensation of neutron absorption for claddings.

Problem tasks

Silicide	Metal	
U_3Si_2 • Production technology	**U-Mo** • Coatings are required to prevent eutectic reactions with the cladding.	**U-Zr** • Significant form change; • Danger of interaction with water and steam.
The consideration of the Doppler effect is required; Lower melting temperature compared to UO_2.		

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Chromium coating

Application method High-Speed Ion-Plasma Magnetron Sputtering (HSIPMS)

Positive properties:

- Oxidation rate of Cr-coated fuel rods at the temperature of 1100-1200°C is the order of magnitude lower than the oxidation rate of zirconium pipes. Mechanical properties of the claddings are preserved after autoclave experiments on oxidation in water at a pressure of 18 MPa and the temperature of 1100-1200°C, (hydrogen brittleness is absent), unlike zirconium claddings;
- Manufacturing implementation requires minimal changes in the existing design and manufacturing technology of fuel elements;
- It is anti-debris plating;
- Provides corrosion resistance under increased power and boiling conditions.

Negative properties:

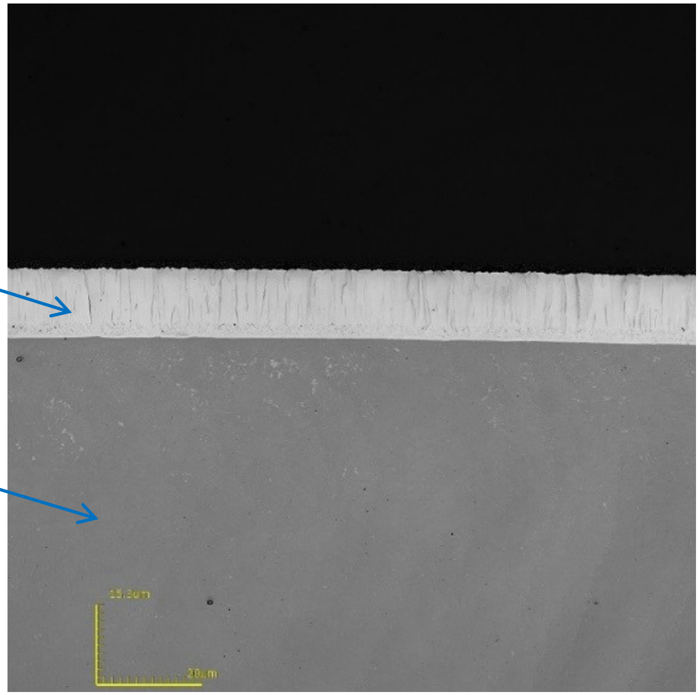
- No experimental data on coating state during irradiation;
- Thermal capture cross section by chrome isotopes (3.05 barns) 15 times higher than that of zirconium isotopes (0.185 barn),
- Production of the active short-lived isotope ^{51}Cr ($T_{1/2}$ = 28 days) and change in the chemical composition as a result of the vanadium accumulation.

Metallographic Observation

Coating thickness control

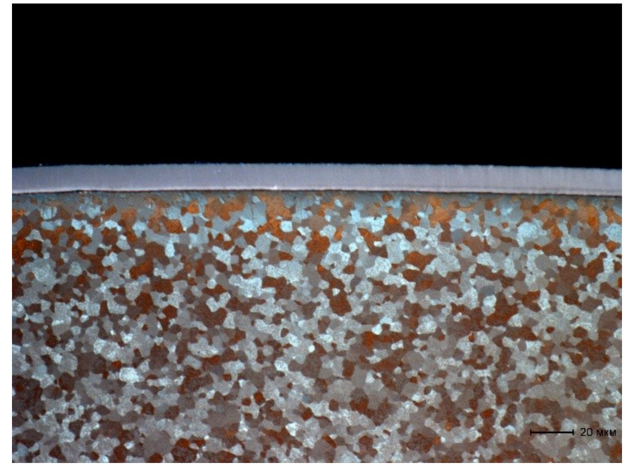
Cr-coating

E110opt cladding tube

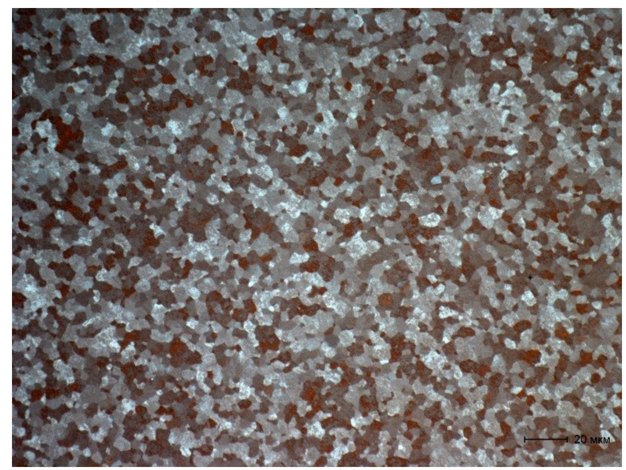


Olympus Lext OLS4000 image

Grain size control on cladding tube outer surface



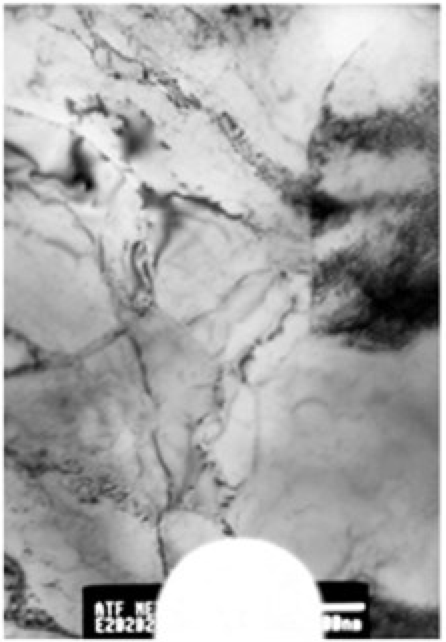
½ wall thickness

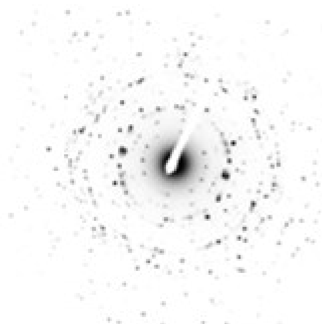


Olympus GX-51 images

TEM Investigations

Transmission electron microscopy images of the protective Cr-coating structure





The average grain size in a chromium coating is at 700 nm. Micro-structure of material presents the matrix of chrome with body-centered cubic lattice.

Results of corrosion autoclave tests of samples with Cr-coating

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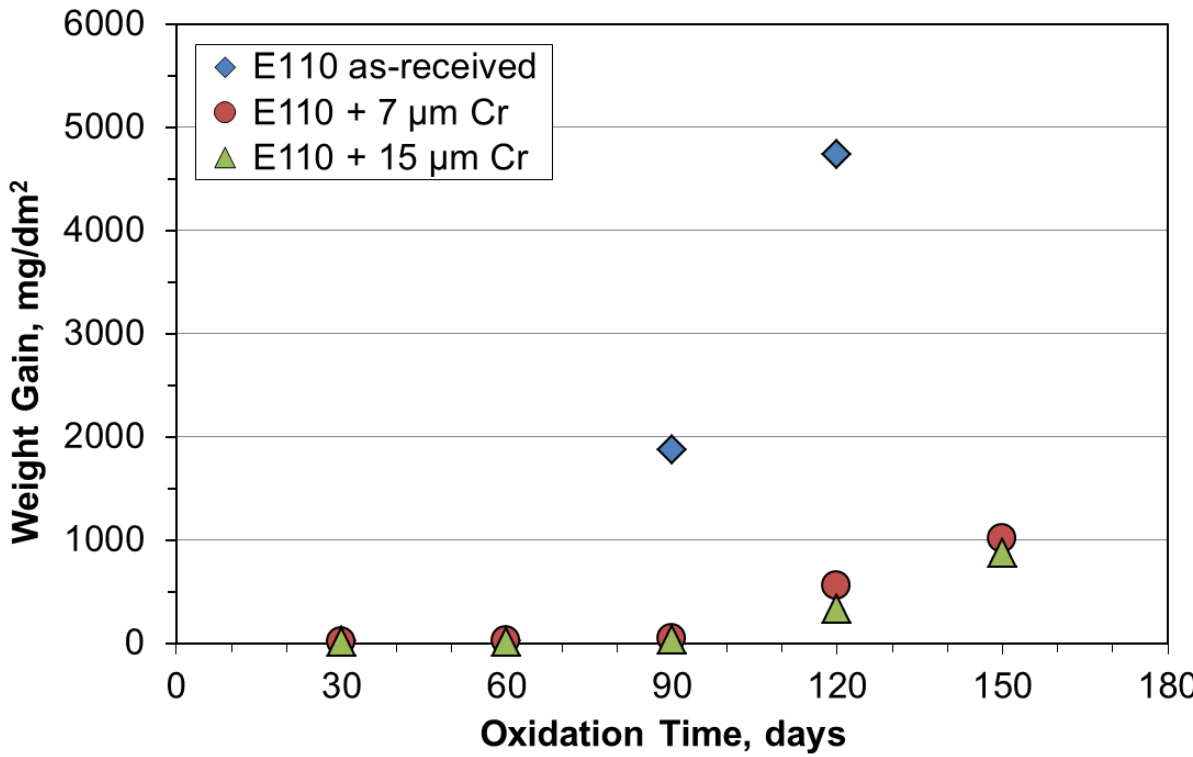

Water + 70 ppm Li
T=360°C
P=18.6 MPa

Results of autoclave tests of E110 samples standard composition based on zirconium electrolytic powder and E110 samples with protective chrome coating

Steam Oxidation Tests at 1000°C

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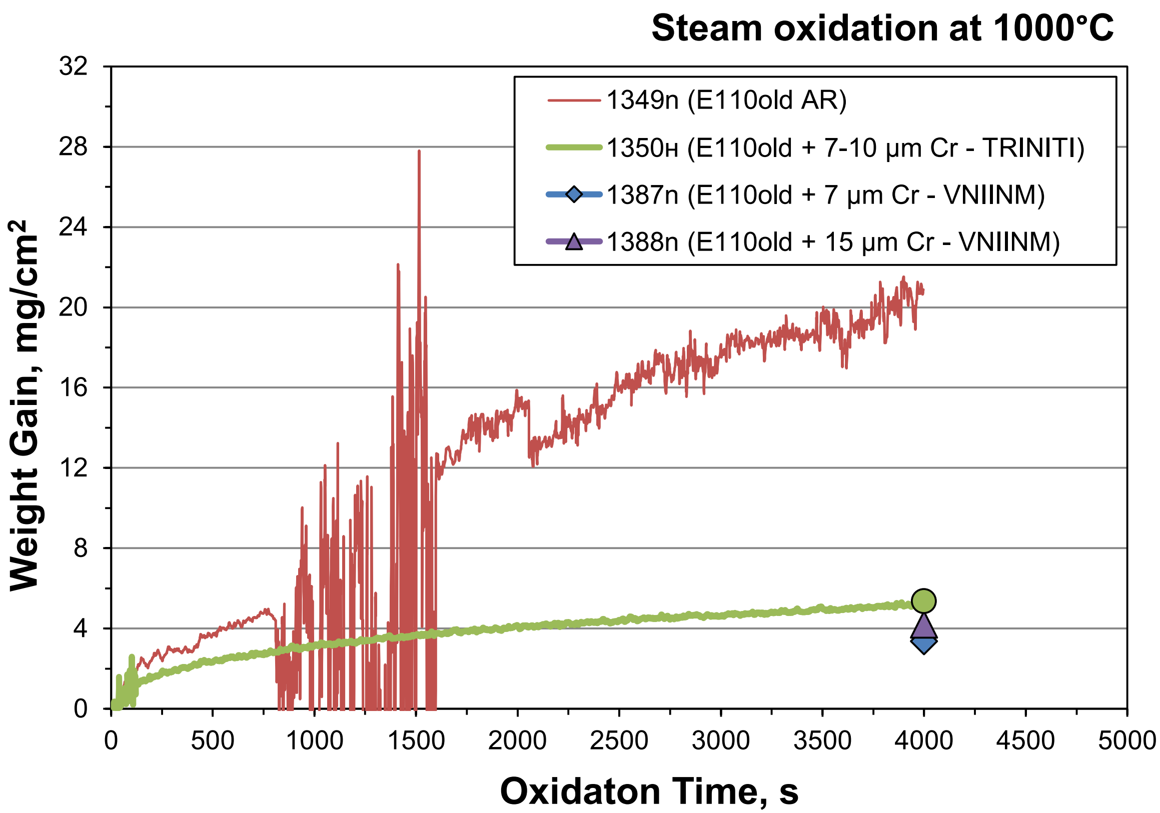
Development of composition and method of application of the protective coating on the fuel rods cladding for accident-tolerant fuel (2016)



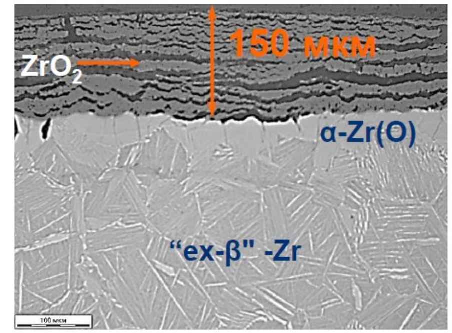


Photo of cross-section area of specimen outer surface without coating after corrosion tests in steam at 1000°C

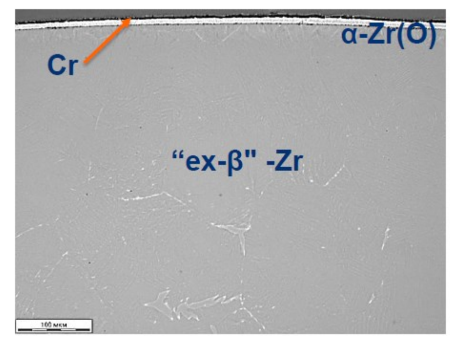


Photo of cross-section area of specimen outer surface with Cr-coating (7 µm) after corrosion tests in steam at 1000°C

Steam Oxidation Tests at 1200°C

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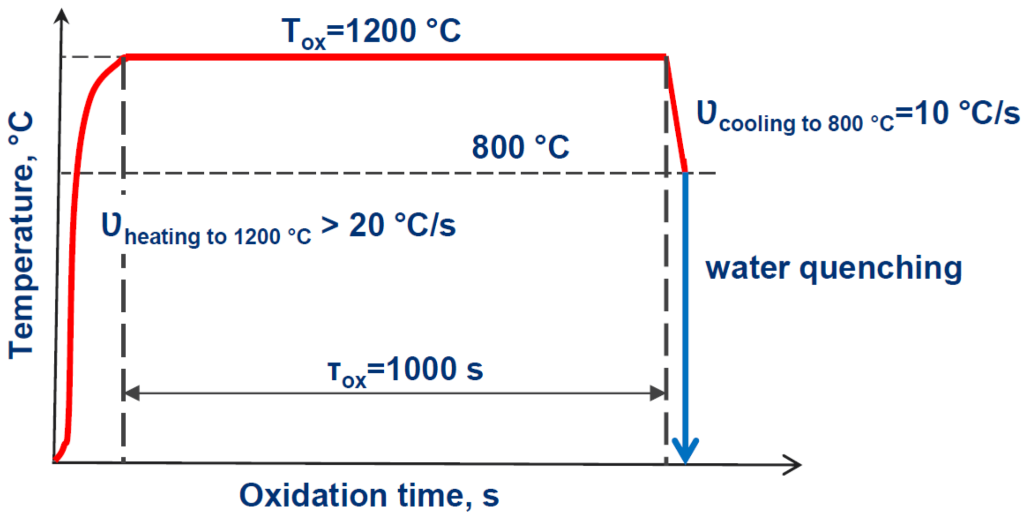
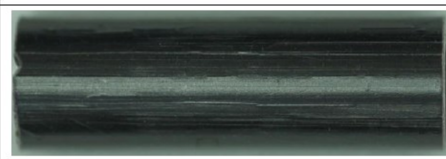
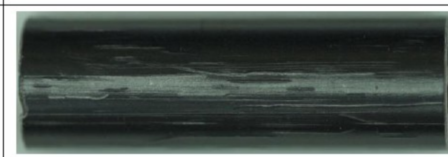
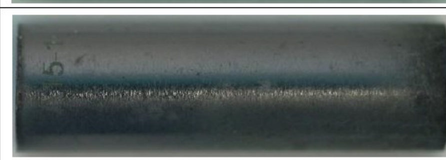
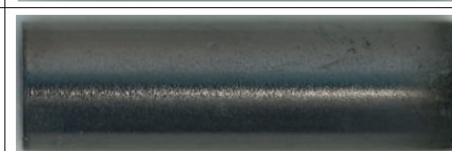
Time-temperature test history



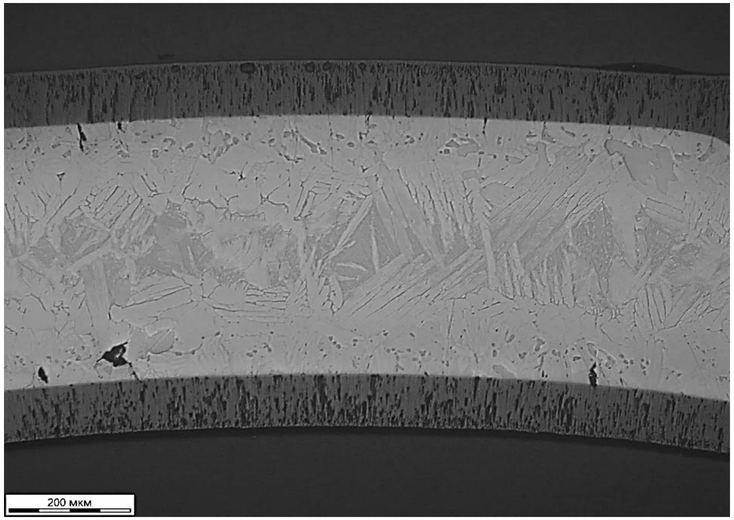
Results of steam oxidation tests at 1200°C of specimens of E110opt alloy with protective coatings

Composition of coating	Thickness of initial coating, μm	Weight Gain, mg/cm²	ECRmeas., %
Without coating	-	19.0	28.5
With coating	**~ 12.3**	**8.9**	**13.4**

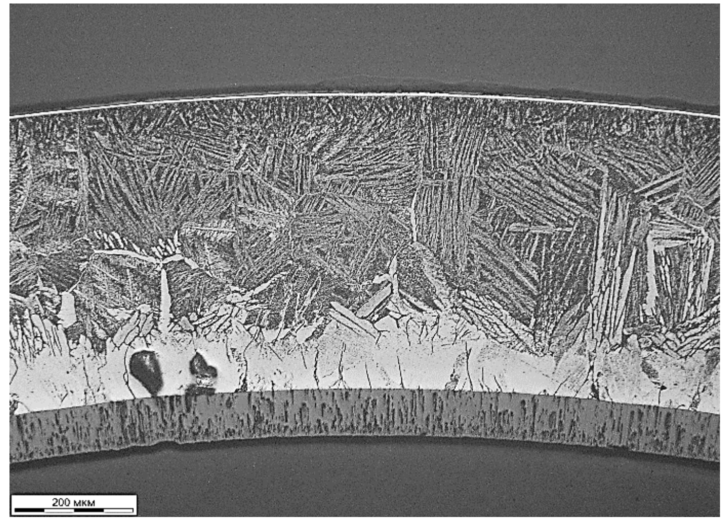
Appearance of samples after steam oxidation tests at 1200°C during 1000 s

Coating Composition	Side A	Side B
As-received (without coating)		
Cr - coating		

Metallographic Observation



E110opt (as-received)



E110opt + Cr coating

Microstructure of the as-received and Cr-coated E110opt samples after steam oxidation test at 1200°C for 1000 s

Post Test Investigations

Samples after oxidation test

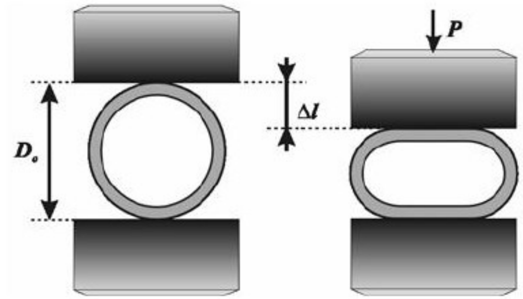
Sample appearance control

Production of metallographic sections

Corrosion (coating) layers measurements

Microhardness measurements

Ring Compression Tests



Testing according to NRC requirements (NUREG/CR-6967, ANL-07/04 Cladding Embrittlement During Postulated Loss-of-Coolant Accidents)

Thin-wall high strength metal claddings

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Claddings from 42KhNM (42CrNiMo) alloy.

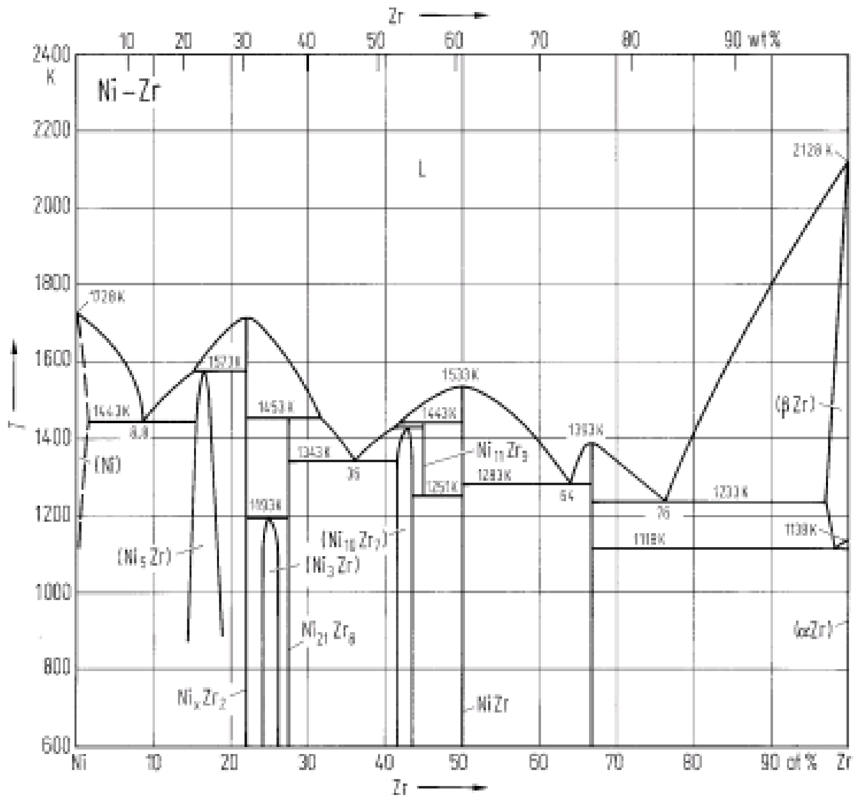
Benefits:

- Low speed of oxidation in water steam;
- Operation experience of claddings of AEs (absorber elements) of VVER.

Disadvantages:

- Increased, thermal neutron capture (Cr - 3.05 barn, Ni - 4.49 barn, Mo - 2.48 barn) in comparison to zirconium cladding. That will require the use of fuel with an enrichment of more than 5% for ^{235}U, or the use of a thinner cladding;
- Ductility reduction at high temperature;
- Change of the chemical composition as a result of irradiation; - production of short-half-life radioactive isotopes of chrome, radioactive cobalt and molybdenum.

Compatibility



Ni-Zr. Phase diagram

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Ceramic claddings (SIC)

Benefits:

- Dissociation temperature SiC (~2545±40 °C) in 2 times exceed the cladding temperature in case of design basis loss of coolant accident;
- Do not react with water steam up to 1300 °C;
- Thermal capture cross section by silicized carbon (Si – 0.171 barn, C – 0.0035 barn) is less than zirconium.

Disadvantages:

- Problems with treatment and usage of claddings associates with their fragility at normal conditions;
- Low creep rate of SiC claddings;
- Problem with sealing of nuclear fuel rods (welding of plug and cladding);
- Expensive production of SiC fibers.

Fuel U_3Si_2

Development of the composition and experimental technology for producing U_3Si_2, study of the properties of the obtained compound
Receiving of granular molding compound U_3Si_2 (2019)
Elaboration of the technology of preparation of granular molding compound of U_3Si_2 (2019)
Development of manufacturing technology for tablet fuel based on U_3Si_2 powder and study of tablet properties (2020)
Pre-reactor investigation of U_3Si_2 tablet properties (2020)

Fuel U_3Si_2

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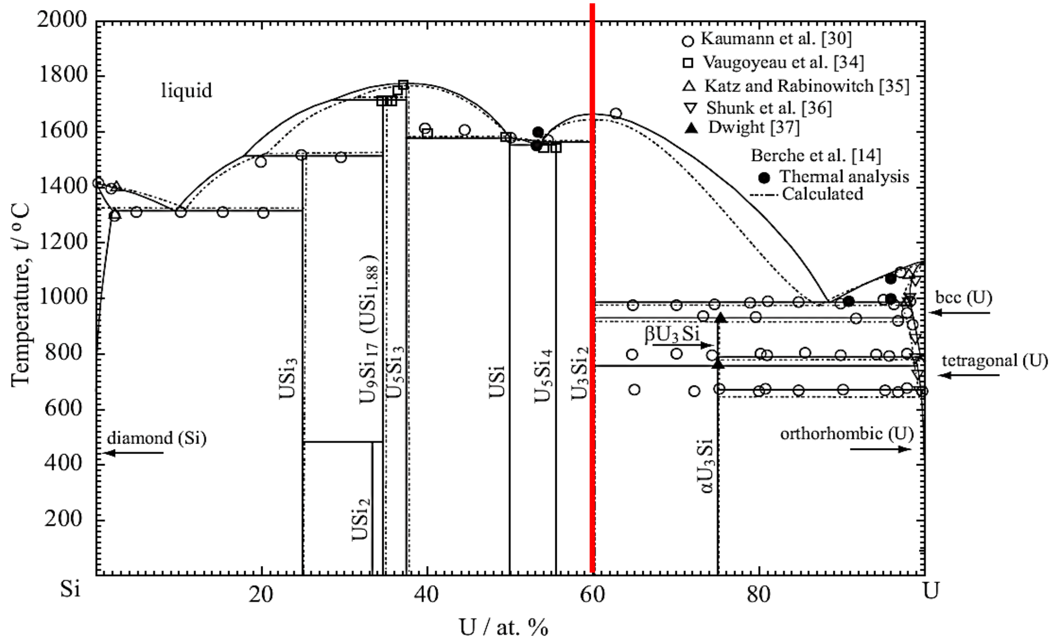


Metal U → **U fine powder** → **Biscuit from powders of U and Si** → **U_3Si_2 slug** → **U_3Si_2 fine powder** → **U_3Si_2 tablet**

Fuel characteristics

Specification	UO_2	U	U-9Mo	U_3Si_2
Theoretical density, g/cm^3	10.96	19.07	17.0	12.2
Density as per uranium, g/cm^3	9.6	18.9	15.3	11.3
Thermal conductivity, W/m· К				
at 200°C	6.9	30.5	16.9	10.0-12.0
at 500°C	4.0	36.0	36.8	12-18
at 1000°C	2.1	-	-	18
Linear coefficient of thermal expansion, x10^{6}K^{-1} (20-200°C)	9	18	17	15.5
Melting temperature, °C	2840	1320	1145	1665
Rate of corrosion in water at 300°C, mg/cm^{2}h	0	1000	0.08	0.01 (at 100°C)
Spurious capture of elements in the compound with uranium, barn/per atom U	0.0004	0	0.68	0.043

Preparation for reactor testing

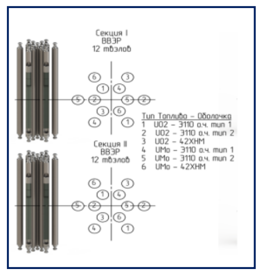
Elaboration of coating technology

Autoclave tests (Water, Steam, Water +Li)

High-temperature steam oxidation test

Coating characteristics

Experimental fuel assembly for MIR reactor



Optimization of 42KhNM tube production technology for PWR

Optimization of U-Mo tablets production technology

Optimization of welding process

Manufacturing of the sealing technology of the cladding E110 with Cr-coating

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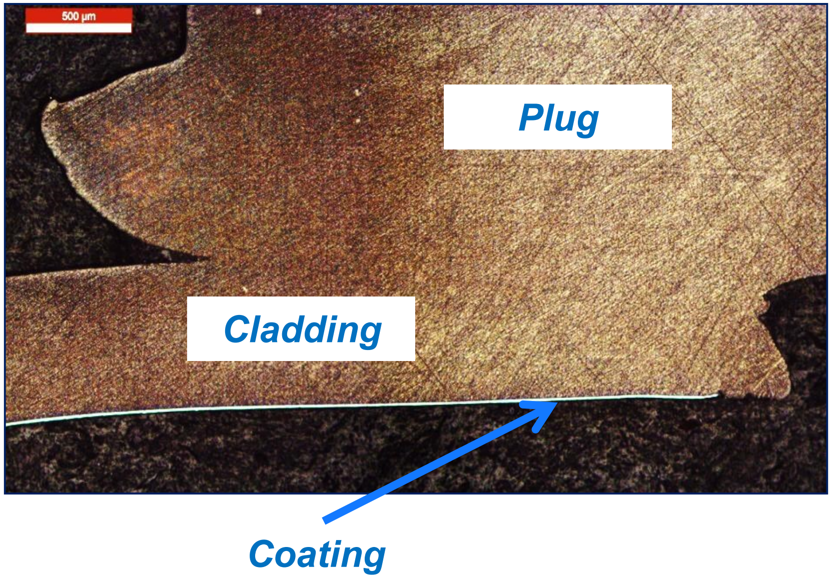

Developing the sealing technology for fuel element cladding with Cr-coating by the KSS-2 method (resistance butt welding).

Tightness of the welded joints meets the requirements

Development of the welding technology KSS-2 of claddings from 42KhNM alloy (42CrNiMo)

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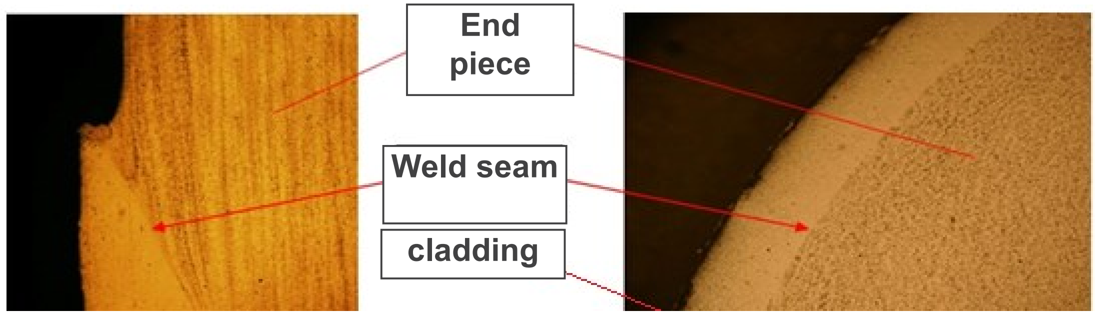
42KhNM welding

There is positive experience of performance of welding connections for cladding from 42KhNM alloy.



Resistance butt welding (KSS-2)

Technology development and production of experimental fuel elements and EFA

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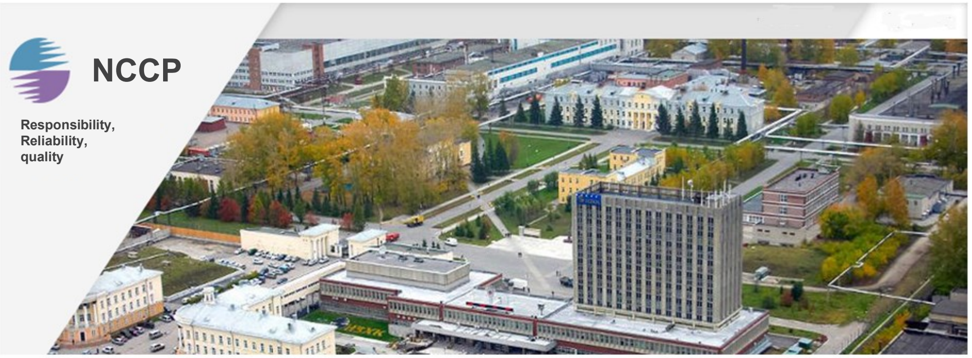
JSC VNIINM has developed the technology for the manufacture of the accident-tolerant fuel (ATF), which is the following combination of structural materials and fuel compositions:

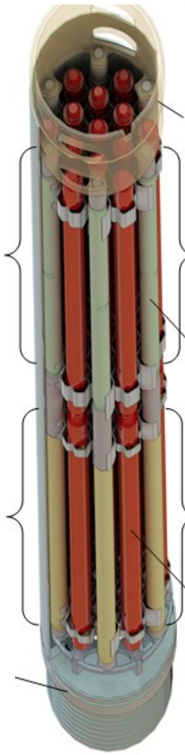
1. Cladding made of alloy E110 coated with chrome-based coating + fuel UO_2;
2. Cladding made of alloy E110 coated with chrome-based coating + fuel U-Mo;
3. Cladding made of alloy 42KhNM + fuel UO_2;
4. Cladding made of alloy 42KhNM + fuel U-Mo.

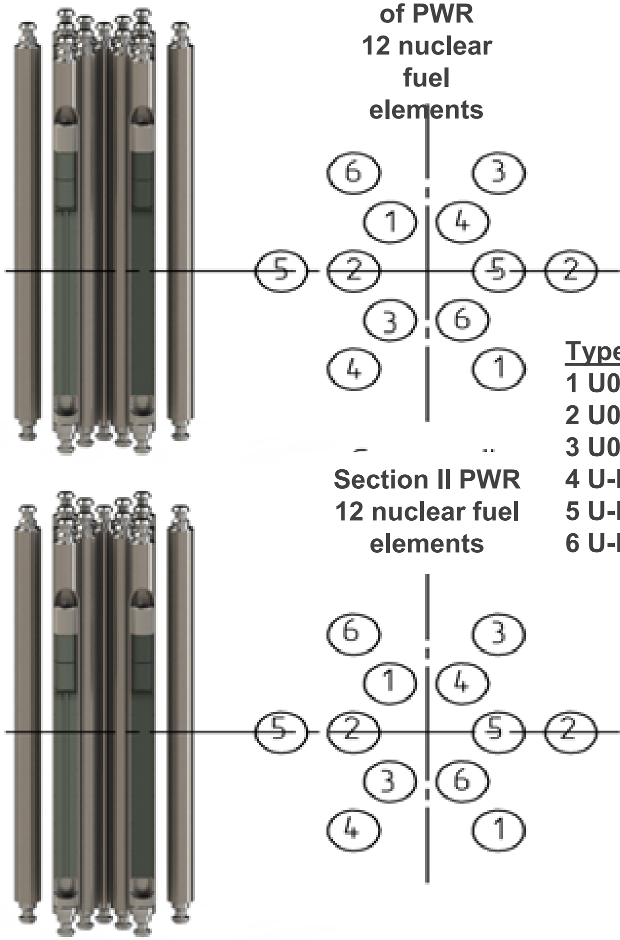
Construction of the experimental nuclear fuel rods and fuel assemblies was designed for manufacturing the above options of accident-tolerant fuel. Two different technologies were developed for applying a chrome-based coating to the cladding of the fuel element, composition and manufacturing technology of metallic U-Mo fuel, and technology was also developed for manufacturing thinned claddings of the fuel elements from 42KhNM alloy. Pre-reactor investigations of claddings with E110 alloy coating, 42KhNM alloy, and U-Mo metallic fuel were performed. Subsequently, experimental ATF fuel rods and two experimental fuel assemblies were manufactured at NCCP (Novosibirsk Chemical Concentrates Plant).

At present, experimental ATF fuel rods are irradiated in the loop channels of the MIR reactor (JSC «SSC RIAR»).

Production of experimental fuel elements and EFA



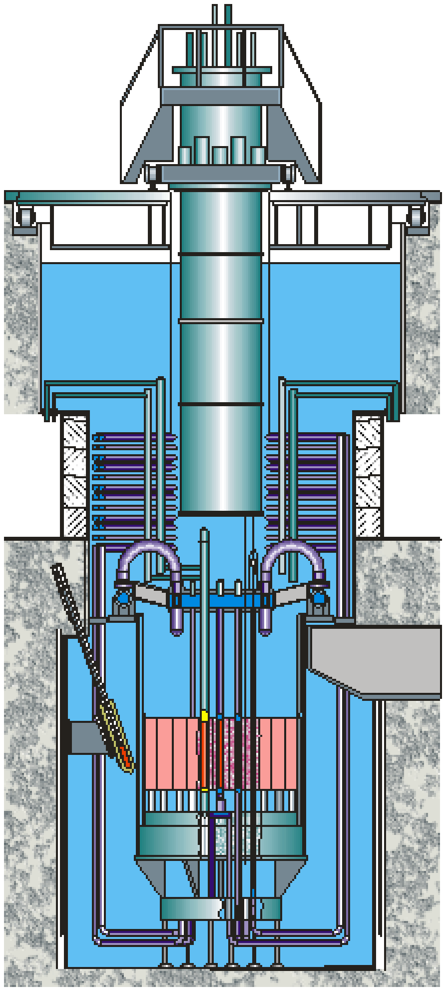


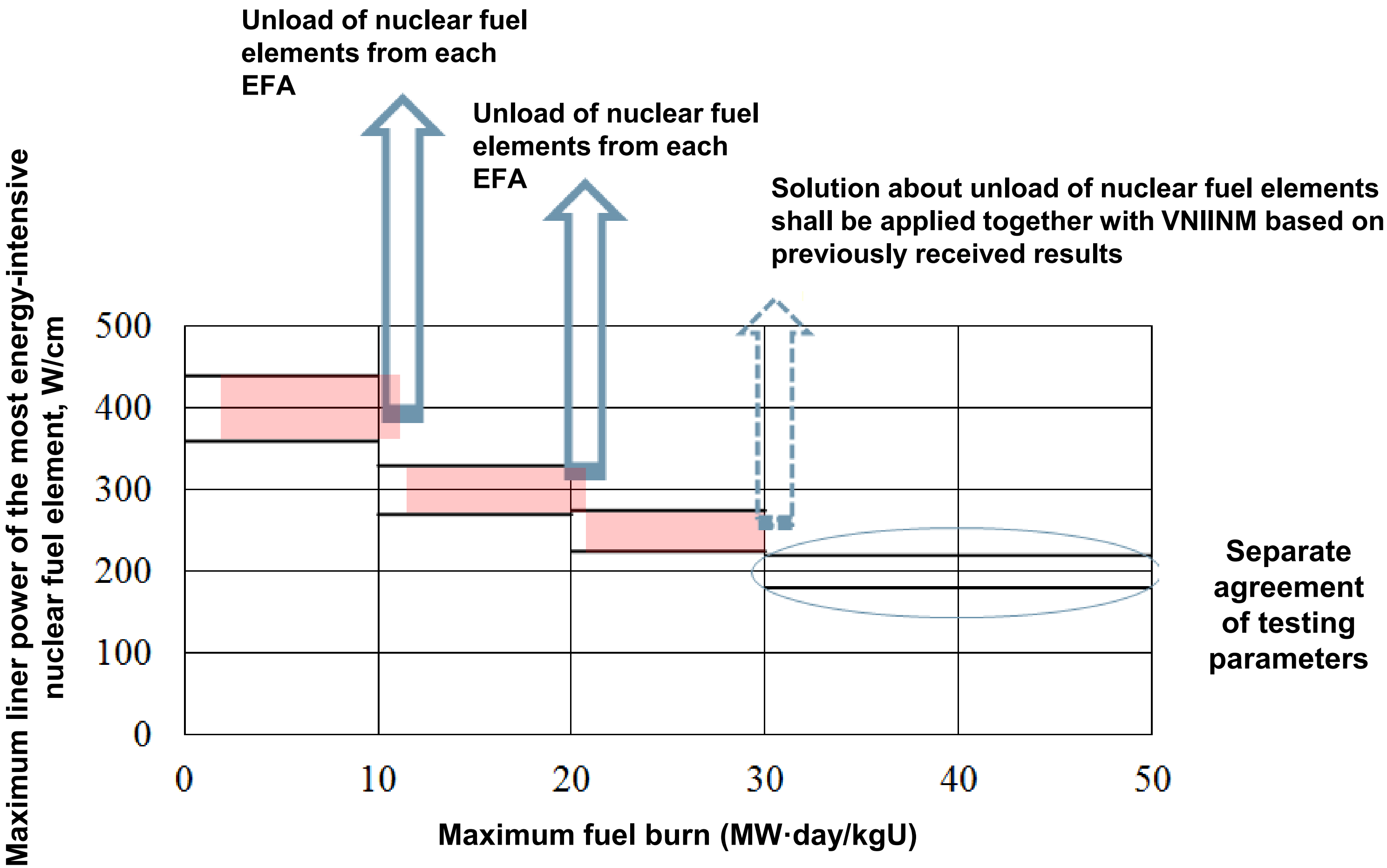


<u>Type Fuel-Cladding</u>

1 U02 - E110 extra-pure grade type 1
2 U02 - E110 extra-pure grade type 2
3 U02 - 42KhNM
4 U-Mo - E110 extra-pure grade type 1
5 U-Mo - E110 extra-pure grade type 2
6 U-Mo - 42KhNM

Usage of the accident-tolerance fuel in the MIR reactor. Program of the reactor usage





Reactor experiments and modelling

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Development of accounting codes

- thermal expansion of fuel;
- changing of Young's modulus and Poison's ratio;
- mechanical properties;
- creep flow;
- thermal conductivity;
- density and heat capacitance;
- additional compaction and swelling;
- outlet of gas fission products;
- changing of structure;
- cracking of reactor fuel pellet;
- high-temperature steam oxidation.

Decision

on the organization of the first stage of putting into pilot operation three combined fuel assemblies-2M with accident-tolerance type fuel rods.

The program of the experimental-industrial pilot production of three TVS-2M with nuclear fuel elements of accident-tolerant fuel type in active section of energy unit No.2 of Rostov NPP in 9-11 fuel element column (2020-2024).

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THANK YOU FOR YOUR ATTENTION