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STRUCTURAL MATERIALS FOR ELEMENTS OF NUCLEAR REACTORS EQUIPMENT

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The paper presents the main results of research on the development of structural materials for equipment elements of existing and prospective nuclear power plants. The further development of nuclear energy largely depends on the development of advanced structural materials for new generation reactors and the improvement of materials for operating nuclear power plants. The results of research on the optimization the iron content of the zirconium alloy to increase corrosion resistance in the coolant and resistance to radiation growth are presented. Experimental determination of the laws of the behavior of impurities during the refining of chemically active and refractory metals made it possible to achieve a higher level of metals purity. It is shown that nickel alloys of the Hastelloy type, obtained from high-purity metal components, can be successfully used as a structural material of the MSRs. The high requirements for structural materials regarding the content of impurity elements can be met only when high-purity metals are used as initial components and new technologies for their production are used.

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INTRODUCTION

Sustainable and affordable energy is crucial to worldwide economic prosperity and stability. Nuclear energy has emerged over the past 40 years to become a reliable baseload source of clean and economical electrical energy.

The core of a nuclear reactor presents an exceptionally harsh environment for materials due to the combination of high temperature, high stresses, a chemically aggressive coolant and intense radiation fluxes. Many of the features that make reactors attractive from a physics perspective (e.g. high specific power, self-sustaining reaction) exert high operational burdens on structural materials.

Recent activities to extend the operating lifetime of current water reactors, to develop advanced fission reactor concepts with greater functionality and capability, and the coming emergence of fusion energy represent even greater demands on materials.

An international cooperative alliance the Generation IV International Forum or GIF was created to study the practicality and performance of Generation IV (GEN IV) reactors to ensure a global, safe, innovative, sustainable and economic energy source [1]. This international alliance selected six emerging nuclear technologies: gas-cooled reactors (GFR and VHTR), molten metal-cooled reactors (LFR), molten salt reactors (MSR), sodium-cooled reactors (SFR) and supercritical water-cooled reactors (SCWR) [1]. These innovative nuclear reactors can guarantee the low-carbon, long-term, safe and economical production of energy.

These nuclear systems use very harsh coolants, the main challenge lies in the identification of suitable structural materials and fuel claddings to withstand the high temperatures, high pressures and radiation. In terms of structural materials, there are some issues, such as resistance to uniform and localized corrosion, dimensional stability to creep at high temperatures and resistance to radiation damage. To select appropriate materials for nuclear reactor components, many types of alloys must be tested tested under simulated operating conditions.

It is well known that increased level of interstitial impurities such as C, N, O and undesirable metallic elements lead to a decrease in mechanical properties, corrosion and radiation resistance of materials, and therefore limits their use in current and future reactors. Evaluation of typical V-4Cr-4Ti alloys under the conditions of neutron irradiation with a fluence of 10^{21} n/cm^2 showed that the activation level of materials with impurities is approximately two orders of magnitude higher than that of alloys with low level of impurities [2].

The use of high-purity metals as initial components of new structural materials should provide the necessary level of operational properties of products made from such materials. Metals used to create some structural materials for nuclear power plants shows in Table 1. The examination of these data made it possible to outline a number of metallic elements that are necessary components for the creation of materials of interest for future atomic energy.

Successful operation of current light water reactors (LWR) and implementation of advanced nuclear energy systems is strongly dependent on the performance of fuels and structural materials.

This paper presents the results of studying the processes of refining refractory and chemically active metals, development of physical principles for improving existing structural materials and creating new ones based on high-purity metals for nuclear power plants.

Table 1

Metals used to create structural materials for nuclear power plants

Metals	Structural materials	Operating temperature, °C
Zr, Nb, Fe, Sn, Hf	Zirconium alloys for fuel cladding of LWRs core; alloys for control rods	up to 350
Fe, Ni, Cr, Mo, Mn	Steels and alloys of various types (austenitic, low-alloy, ferritic/martensitic steels; nickel-based and other alloys)	up to 700
V, Cr, V	Low-activated alloys	up to 700
Ni, Mo, Cr	High-temperature and corrosion-resistant steels and alloys	up to 850
Nb, Ta, Mo, W, C	Modern high-temperature and refractory alloys, composite materials	above 700

ZIRCONIUM ALLOYS

Due to combinations with a low thermal neutron capture cross section, excellent corrosion resistance in high-temperature water and adequate mechanical properties, Zr-based alloys are widely used as materials for all commercial LWR fuel cladding. The motivations to achieve acceptable safety margin and higher burnup are driving the evolution in the reliability of Zr-based cladding, thereby contributing to the birth of advanced Zr-based alloys like E635, ZIRLO, M5, MDA, etc., which strode a major step forward in improvement of corrosion resistance and mechanical performances. However, the well-known inherent demerits of Zr-based alloys such as rapid oxidation and hydrogen production at high temperature steam, which was highlighted further by the nuclear accident, happened at the Fukushima Daiichi plants.

Corrosion of zirconium alloy cladding is a crucial process that limits the use of the fuel element.

The life limit of Zr-based cladding is usually determined by its corrosion properties, i.e., oxidation in the hot reactor coolant, and in particular the associated absorption of hydrogen.

Cladding tubes are the vital part of a nuclear reactor because they not only provide an enclosure to the highly radioactive fuel but also remain in direct contact with the coolant during reactor operation which makes it vulnerable to corrosion [3]. Hence, the material used for cladding tubes must have the important characteristics as follows; low thermal neutron capture cross-sections, high thermal conductivity, high strength, and high corrosion resistance.

At normal operating reactor temperature (300 °C), Zr is an exceptional substance and has been employed as fuel cladding tubes since the early 1950’s because it has much lower neutron absorption cross section as well as adequate mechanical properties than the other commercially available structural materials.

To get additional properties for better operation in water cooled reactors, Zr was alloyed with constituents which have low nuclear impacts like Sn, O, and Nb, while other transition metals (Fe, Cr, Ni, etc.) can be accepted up to limited concentrations (below 0.5 wt.% total).

Up to date, although many Zr-based alloys have been studied for potential usage in nuclear reactors, only a few of them are of commercial importance, and new Zr-based alloys are continuously developed and then are recommended to be candidates for the advanced nuclear power plant. However, the development of advanced fuel claddings is a persistent issue in the nuclear power area and many investigators have been developing new alloy compositions or exploring new processes for improving performances of Zr-based alloys.

To improve the performance properties of zirconium alloys, it is necessary to optimize the iron content (increases corrosion resistance in the coolant and resistance to radiation growth), and also use zirconium sponge as the alloys base, since such alloys meet safety criteria under LOCA conditions.

To implement the process of obtaining sponge zirconium in Ukraine were developed a process and an apparatus for the production of metal zirconium by the reduction of zirconium tetrachloride by magnesium [4].

The technology of magnesium-thermal production of spongy zirconium on laboratory installations has been studied. The processes for obtaining spongy zirconium are considered: reduction of zirconium tetrachloride and high-temperature vacuum sublimation of the reaction mass [5].

The change in the content of impurities during the refining of magnesium-thermal the zirconium sponge was investigated using the electron beam melting method. It is shown that the content of impurities, except for gaseous ones, in the obtained sponge and the quality of metal zirconium slightly differ from the sponge zirconium of other manufacturers [6].

The results of the research can be used to develop an industrial magnesium-thermal technology for the production of spongy zirconium and equipment for its production.

Additional iron alloying of zirconium and the Zr-1%Nb alloy is promising in the development of alloys for reactors with high reliability and safety of operation, since an increase in the iron content in the zirconium alloy provides the material of the cladding tubes with the necessary creep resistance and hardening under irradiation, which ensures the design margin of stability and increases its corrosion and radiation resistance in the conditions of the nuclear reactor operation [7].

Research on the improvement of structural zirconium materials (Zr-1%Nb alloys) by optimizing the amount of the alloying element iron were carried out. The influence of the iron content in the Zr-1%Nb alloy on the corrosion, radiation and mechanical properties and microstructure of the alloy was studied.

Samples of the Zr-1%Nb alloy based on magnesium-thermal spongy zirconium containing iron from 0.012 to 0.192 wt.% with an interval of 0.03 wt.% were used for researches.

The properties of alloys are determined by their structural-phase state and even small changes in the composition of Zr-Nb alloys lead to significant changes due to the appearance of different types of precipitates and changes in the matrix composition [7].

The evolution of the structure of the Zr-1%Nb alloy with increasing iron content has been studied by a scanning electron microscope JSM7001F. It is shown that small additions of iron to the Zr-1%Nb alloy lead to a change in its structure due to the appearance of Laves phase precipitates. It was found that the number of Laves phase precipitates is determined by the Fe content in the alloy and increases with increasing Fe content.

The microhardness of the Zr-1%Nb alloy increases with increasing iron content. An increase in the iron content in the Zr-1%Nb alloy leads to an increase in the microhardness of the alloy. The value of microhardness for alloy samples with 0.012% Fe is 1720 MPa, for samples with 0.072...0.132% Fe – 1750...1760 MPa. And increase in the Fe iron content from 0.132 to 0.192 wt.% leads to a sharp increase in microhardness up to 1880 MPa [7].

Long-term corrosion tests of samples of the Zr-1%Nb alloy with different iron content, obtained by Ukrainian technology, in the water environment with composition and parameters (temperature 350 °C, pressure 16.5 MPa) corresponding to the coolant of the primary circuit WWER-1000 were carried out. The kinetics of weight change of samples of zirconium alloy with iron content from 0.012 to 0.162 wt.% was determined and it is shown that the additional microalloying of the alloy with iron makes a significant contribution to increasing the corrosion resistance of the Zr-1%Nb alloys [8]. The graphical dependence of the change in the corrosion rate of zirconium alloy samples on the iron content is shown in Fig. 1.

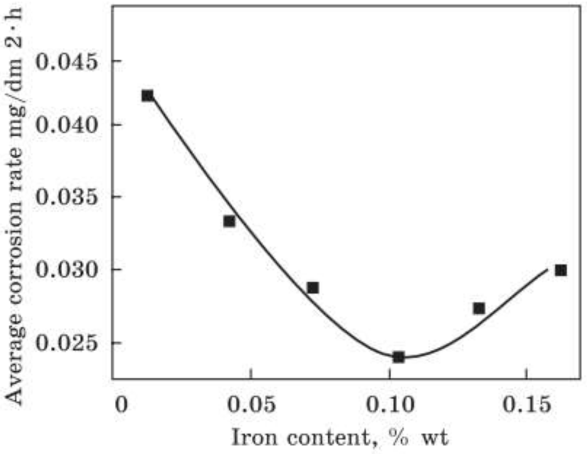

Fig. 1. Average corrosion rate of Zr-1% Nb alloy samples depending on the iron content during 1500 h of testing in an aqueous environment at a temperature of 350 °C and a pressure of 16.5 MPa

Mathematical processing the results of experimental corrosion studies made it possible to determine the optimal Fe content, which will increase the corrosion resistance of the Zr-1%Nb alloy under operating conditions in the WWER-1000 core [9]. The optimal amount of iron, which will increase the corrosion resistance of the Zr-1%Nb alloy under operating conditions in the core of WWER-1000, is 0.1 wt.%.

Ar^{2+} ions irradiation at temperature of 390 °C and an irradiation doses 5 and 15 displacements per atom (dpa) of the Zr-1%Nb alloy with different Fe content showed that increasing the Fe concentration leads to the decrease in the size of the interstitial dislocation loops and a slight increase in their density [10].

X-ray microspectral studies of the composition of second phase particles in samples of the Zr-1%Nb alloys with Fe additions after irradiation to 15 dpa showed that, the precipitates of the Laves phase contain only 1…8% Fe; the content of Fe in the precipitates of the Laves phase was 30% before irradiation. During irradiation, the Fe release from the precipitates of the Laves phase, diffuse through the matrix and form secondary radiation-induced fine precipitates, which delay in <c>-type dislocation loops nucleation responsible for the acceleration of radiation growth. The Fe alloying of the alloys of the system Zr-Nb contributes to the suppression of the phenomenon of radiation growth in commercially effective ranges of radiation doses [10].

HAFNIUM

One of the components of the production of nuclear fuel and the operational safety of nuclear power plants is the production of absorbing materials for control rods of reactor control and safety system.

In WWER reactors as in similar reactors PWR the clustered assemblies of control rods of reactor control and safety system serve as reactor control.

A noticeable increase in the service life of cluster assemblies of reactor control and safety system can be achieved if a combined (n, α)-(n, γ)-absorber is used. Hafnium is a (n, γ)-absorber and in the future can serve as both a neutron absorber and a structural material.

The physical-mechanical properties of hafnium significantly affected by the presence of impurities, so to improve the quality of hafnium was carried out complex of research works on improving processes of producing hafnium of nuclear grade [11].

The processes of producing reactor-grade hafnium are investigated. It is shown that the electron beam melting (EBM) method is effective for purification of hafnium from metallic impurities. The final impurity concentration was calculated by setting the initial concentration and the time was determined for which the impurity concentration decreases to a predetermined value, i.e. melting parameters [12].

Calculations were performed for the impurities of Fe, Al, Cu, Ni, Ti, Si, Cr, etc. As an example, Fig. 2 shows the results of calculating the change in the concentration of Fe in hafnium from the exposure time in the molten state at various temperatures. Calculations also showed that removal of the impurities is reduced in a series of Zn > Be > Mn > Cr > Cu > Al > Fe> V > Co > Ni > Si [12].

The obtained parameters were used to optimize the EBM of hafnium in laboratory and experimental industrial conditions. After two successive EBM was obtained hafnium with purity >99.95 wt.%.

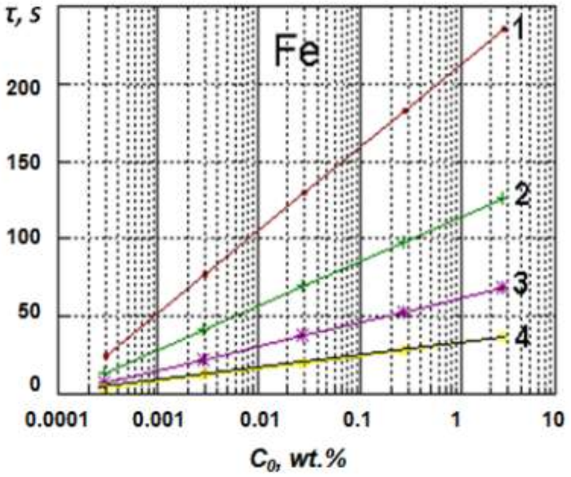

Fig. 2. The change in the concentration of Fe in hafnium from the exposure time in the molten state at a temperature: 1 – 2505; 2 – 2600; 3 – 2700; 4 – 2800 K

Great difficulty in obtaining of nuclear grade hafnium is purification from interstitial impurities − nitrogen and oxygen. Based on the analysis of literature data and taking into account obtained results of laboratory studies aluminum was chosen as a hafnium deoxidizer. The use of aluminum as a deoxidizing component on the reduction melting stage of hafnium results in essential decrease the oxygen content in the metal (to 0.03…0.04 wt.%) on the EBM stage [12].

Carrying out of vacuum thermal treatment of hafnium tetrafluoride before the reduction melting in the temperature range of 300…600 °C provides a nitrogen content in the metal less than 0.005 wt.%.

Thus the research results of refining hafnium allow carrying out the scientific approach to producing of hafnium with low oxygen and nitrogen content for modern technologies and creating of structural materials for nuclear reactors of the new generation and other responsible applications [12].

HIGH-PURITY COMPONENTS FOR PROMISING ALLOYS

For obtaining pure metal at different stages of refining use various chemical and physical-chemical methods, but usually the refining process complete physical methods – distillation, zone recrystallization, electrotransport, and various combinations thereof. These methods are mainly physical processes: evaporation and condensation, crystallization, diffusion and electromigration, etc [13]. The advantages of these methods over the other associated with the ability to achieve high purity and obtain of the final product in a compact form, including single crystals with a perfect crystal structure.

Below are the results of experimental physical methods refining of some metals, which are important components for the production of new alloys for nuclear power [14]. For research of physical and chemical refining processes used metals, differing in initial degree of purity and methods of preparation.

Vanadium and titanium are important components for the production of low-activity alloys for nuclear power. The activation level of these alloys will be depending on impurity contents in alloys [15]. So obtaining high-purity components (V and Ti) for low-activity alloys is relevant today.

Studies have shown that carrying out EBM of electrolytic vanadium reduces the content of metallic impurities in it, although almost no purification of Fe and Ni, and even increasing the amount of Si [15]. Carrying out zone melting (ZM) can effectively remove impurities of Al, Fe, Ni, Cu, and Cr. Si is removed slightly. Impurities of refractory metals (W, Mo, Ta, and Nb) during long recrystallization vanadium accumulated in it.

Table 2 compares the effectiveness of purification of technical purity V rods by methods of EBM and zone melting (ZM). The data in Table 2 show that ZM is a more effective method for purification of V samples than EBM. Si content in a technical metal is high, and it is the limiting impurity for the ZM process.

Table 2

The content of impurities in the vanadium after EBM and ZM

Type of metal	Content of impurities, ppm						
	Fe	Cr	Cu	Mo	Si	Mg	Al
Initial	1000	30	5	60	1500	16	200
After EBM in vacuum $5 \cdot 10^{-4}$ Pa	200	<30	2.4	40	1500	5	20
After ZM in vacuum $2 \cdot 10^{-5}$ Pa	17	<30	<1.4	20	1300	<0.5	<10

The most pure vanadium was obtained by refining electrotransport method on metal wire samples [15]. Studies have shown that in vanadium when passing a constant electric current of high density of the interstitial impurity migrating to the cathode side of the sample.

Interesting to carrying out the vacuum distillation of vanadium, which can reduce the silicon content in the metal is more than ten times, and effectively get rid of the impurities of refractory metals [15].

Titanium ingots with diameter of 150 mm and purity 99.99 wt.% were produced by method EBM using sponge TG-90. Analysis of the results of experimental melting of titanium sponge TG-90 showed that the hydrogen content of Ti after EBM decreased by 4.5 times compared to the initial concentration and the concentration of O and N was significantly decreased.

Impurity content in the obtained Ti ingots is much less than required by the standards for titanium.

More pure Ti was obtained after EBM of the initial titanium, which was received by iodide refining (iodide titanium).

Ti refining by zone recrystallization method in an electric field made it possible to significantly reduce the content of both metallic and gas-forming impurities. The oxygen concentration was reduced by 2.2, carbon by 3.3, nitrogen by 22 times [15].

Investigation of regularities refining of V and Ti allowed reaching a higher level of purity metals by applying methods of electron-beam melting, zone recrystallization and electrotransport in vacuum. Suggested methods for obtaining high-purity metals have created the necessary prerequisites for their use in improving existing and producing new structural materials.

Refining of the starting Fe materials was carried out by EBM method. The Brinell hardness of the initial samples of Armco iron was 830 MPa, after refining 624 MPa. The impurity contents in carbonyl iron after EBM are shown in Table 3. Changing the content of impurities in the carbonyl iron as a result of the EBM shows that the impurities of Co and Ni are most difficult to remove from Fe. The Brinell hardness of samples of carbonyl iron after EBM was 558 MPa.

Reduce their content to a lower level has provided distillation method. Distillation of carbonyl iron remelted by EBM it possible to obtain metal purity more than 99.98 wt.%. The purity level of Fe is largely determined by the content of Ni and Co [16].

Table 3

Content of impurities in carbonyl iron

Impurity	Content of impurities, x10^3, wt.%		
	Initial	After EBM	Distillate
Mn	120	2	0.1
Al	20	10	0.3
Cu	150	10	4
Co	17	17	8
Ni	150	100	20
Si	200	50	2
C	50	10	1
O	30	20	2
N	6	3	<1

Double EBM in a high vacuum of initial electrolytic nickel allowed to obtain metal with purity 99.994 wt.%. As a result of refining was decreased content of Fe, Co, P, Al, Mg and the concentration of As, Zn, Se, Cl was decreased significantly. The effectiveness of the method of refining nickel by EBM experimentally demonstrated as for metallic impurities, and for interstitial impurities.

Studies of the nickel microstructure showed that the structure of nickel after EBM consist of large equiaxed grains ~ 3.2 mm in size in the central part of the ingot and small ones, elongated ~ 0.13 mm in size in the peripheral part (Fig. 3). There are accumulations of impurities along the grain boundaries in nickel after the first remelting (see Fig. 3), and the grain boundaries are clean after the second remelting, there are no accumulations of impurities along them, and the number of inclusions significantly decreased, indicating that efficiency of refining nickel by method EBM.

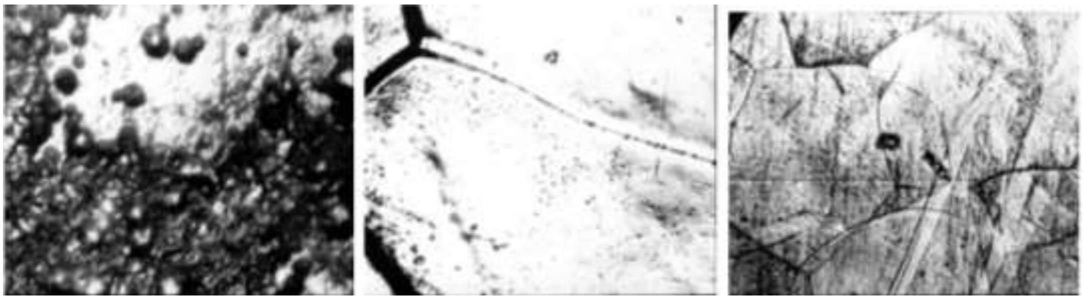
a *b* *c*

Fig. 3. The microstructure of nickel:
a – initial (x110); b – after the first EBM (x100); c – after the second EBM (x145)

Carrying out EBM of nickel leads to reduction of the content of interstitial impurities: oxygen, nitrogen, carbon up to 0.0005, 0.00006, and 0.002 wt.%, respectively. Such interstitial impurities content has practically no effect on the properties of nickel. Proof of this is research of hardness of nickel. The hardness decreases with 1690 MPa for the initial nickel up to 800...900 MPa for nickel after two EBM due to increasing purity of metal. High-purity single crystals of nickel by the relative residual resistivity RRR = 1000 and microhardness 950 MPa were obtained by zone melting. Studies have shown a significant improvement in the quality of the metal after refining [16].

As the initial material were used powders and rods of tantalum purity of 99.8 wt.%. Vacuum electron beam melting reduces the content of metallic impurities in the tantalum compared to their content in the initial material by one or two orders of magnitude, and significantly reduces the content of interstitial impurities. Degassing and evaporation of volatile impurities are the main purification processes of tantalum by EBM [17].

To improve the efficiency of refining tantalum from impurities and produce single crystals of tantalum used float-zone melting in an ultrahigh vacuum and controlled (active) environment and zone melting with electrotransport. Single crystals of tantalum obtained by zone melting in a controlled environment of oxygen had 99.999 wt.% [18].

As a result of zone refining were obtained oriented single crystals of tantalum diameter 7...10 mm and length 150...180 mm with disorientation elements of substructure <0,01° and microhardness 750 MPa [18].

MATERIALS FOR NEW GENERATION REACTORS

The safety, reliability and efficiency of new generation reactors will largely be determined by the behavior of structural materials operating under harsh conditions. Structural materials must provide the required level of operational properties of structural elements of promising nuclear power reactors.

Low-activated V-Cr-Ti alloys are candidates for high-performance structural materials for the first-wall and blanket components of fusion reactors and structural materials for cores of fission (fast) nuclear reactors, because of their high temperature strength, irradiation resistance, low induced radioactivity, high thermal conductivity, and compatibility with lithium coolant [19].

One of the critical issues that should be addressed is the need for a reduction of O, C and N interstitials and precipitates on the mechanical properties, and the control of high-activation impurities (e.g., Ag, Mo, Nb).

It is well known that increased level of interstitial impurities such as C, N, O would result in loss of workability, weldability and irradiation resistance. On the other hand, increased level of undesirable elements such as Co, Nb, Ag, Al, etc. would dominate the activation level of vanadium alloys which would substantially influence not only the recycling aspects of used reactor materials but also the waste management aspects of them [20].

One of the main activities is to reduce and to minimize the impurity level of the commercial vanadium and its alloys.

In recent years, research aimed at the development of new structural materials that can be used in the operational conditions of promising fusion and fission reactors has been actively conducted at the NSC KIPT.

Currently, research is being carried out to produce high-purity alloys of the V-Cr-Ti system using high-purity metals in order to minimize the induced activity of the alloys and increase their radiation resistance in the operation of fussion reactors [2, 21].

Research is also being carried out on the development and selection of structural materials for super critical water-cooled reactor (SCWR) based on high-purity metals (Fe, Ni, Zr, etc.) and studying their performance under the service conditions of such reactors (25 MPa, 500°C). Some high performance zirconium alloys may be of possible use in relatively low temperature SCWR reactor design.

The problems with the selection of materials resistant to higher outlet temperatures exist in the case of the molten salt reactor (MSR). The temperature of the coolant (fluorine salts) is from 700 °C (at very low pressure) up to 800 °C [22]. For MSR systems operating under these conditions, mainly preexisting alloys have been proposed, namely Ni-based alloys, Nb-Ti alloys, modified Hastelloy N and graphite. To date, tests carried out in fluoride salts at temperatures up to 800 °C have proven that modified Hastelloy N is resistant to corrosion under these harsh conditions [22]. Additionally, nickel-based alloys have proven to be suitable structural materials for MSRs due to their strong, stable, corrosion resistant and good welding characteristics.

The use of high-purity metals (Ni, Mo, Cr, Ti, Al, Fe, Mn, Si) as initial components, the use of high vacuum and purified argon made it possible to obtain samples of the high nickel-content alloys (Hastelloy type) with a low content of undesirable impurities [23]. The initial components were purefined, using various physical techniques. The content of the alloys: Ni – base, Mo – 11.7; Cr – 6.7; Ti – 0.47; Al – 0.83; Fe – 1.5; Mn – 0.5; Si – 0.15 wt.%.

Samples of the alloys of Hastelloy type were irradiated with electron beam with the average energy 9.6 MeV in the melt of sodium and zirconium fluoride salts (ZrF_4+NaF_4) at the temperature 650 °C for 700 h [24]. Studies of the Hastelloy specimens irradiated in the molten salt for 700 hr at 650 °C showed that the depth of intercrystalline corrosion essentially depends on the deposited energy (E_d). The depth is 25…30 µm at E_d=5066 eV/at and 5…10 µm at E_d=64 eV/at.

The data show considerable dependence of the intercrystalline corrosion on the alloy composition alsow. The Hastelloy specimens alloying with 0.5 wt.% Nb and 0.05 wt.% Y improves the corrosion resistance of the alloy.

The irradiation of the samples acts to deteriorate their mechanical characteristics. The addition of niobium and yttrium to the alloy enhances the mechanical properties of this alloy after irradiated with electron beam in the melt of fluoride salts [24].

The results of the tests, as well as the study of the structure and composition of Hastelloy-type alloys, produced on base of high-purity metals, indicated that they can be successfully employed as structural materials in MSRs.

Using interval analysis methods, interval statistics, and interval polynomial regression models, developed based on the machine learning theory as components of artificial intelligence systems for processing and analysis of the physical laboratory experiments results are a promising direction. The experimental data on the study of the reactor structural materials can be dissimilar and contradictory. Therefore, to make a decision, researchers often have incomplete information about the numerical values of the structural materials' characteristics or they only know the ranges of characteristics possible values.

The prospects for using new methods for evaluating and improving the physico-mechanical and physico-chemical properties (microhardness, corrosion resistance, radiation resistance, etc.) of structural materials of nuclear reactor were substantiated and analyzed.

Modeling using the mathematical models of interval and regression analysis (polynomial regression, ridge regression) as components of machine learning for processing data from experiments on the assessment of the properties of structural materials was used [25, 26]. Studies carried out to solve the problems of determining the dependence of the properties of alloys on various factors have shown that this approach makes it possible to increase the correctness of assessing the physico-mechanical and physicochemical properties of structural materials for nuclear reactors.

CONCLUSIONS

The paper presents the main results of research on the development of structural materials for equipment elements of existing and prospective nuclear power plants.

The further development of nuclear energy largely depends on the development of advanced structural materials for new generation reactors and the improvement of materials for operating nuclear power plants; zirconium alloys and hafnium of high purity are needed to improve fuel assemblies and control and protection systems for reactors of operating nuclear power plants; new high-temperature, corrosion- and radiation-resistant structural materials are the basis for the structural elements of new generation reactors, ensuring their high performance characteristics.

The optimization the iron content of zirconium alloy for increases corrosion resistance in the coolant and resistance to radiation growth was carried out, and the technology of magnesium-thermal production of spongy zirconium on laboratory installations has been studied. Computational and experimental studies of refining processes made it possible to obtain nuclear-purity hafnium. Experimental determination of the laws of the behavior of impurities during the refining of chemically active and refractory metals made it possible to achieve a higher level of metals purity. It is shown that nickel alloys of the Hastelloy type, obtained from high-purity metal components, can be successfully used as a structural material of the MSRs.

The high requirements for structural materials regarding the content of impurity elements can be met only when high-purity metals are used as initial components and new technologies for their production are used.

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КОНСТРУКЦІЙНІ МАТЕРІАЛИ ДЛЯ ЕЛЕМЕНТІВ ОБЛАДНАННЯ ЯДЕРНИХ РЕАКТОРІВ

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Наведено основні результати досліджень з розробки конструкційних матеріалів для елементів обладнання діючих та перспективних АЕС. Подальший розвиток атомної енергетики значною мірою залежить від розробки перспективних конструкційних матеріалів для реакторів нового покоління та вдосконалення матеріалів для діючих АЕС. Наведено результати досліджень по оптимізації вмісту заліза у цирконієвому сплаві для підвищення корозійної стійкості в теплоносії та стійкості до радіаційного росту. Експериментальне визначення закономірностей поведінки домішок при рафінуванні хімічно активних і тугоплавких металів дозволило досягти більш високого рівня чистоти металів. Показано, що нікелеві сплави типу Hastelloy, отримані з металевих компонентів високої чистоти, можуть бути успішно використані як конструкційний матеріал РСР. Високі вимоги до конструкційних матеріалів щодо вмісту домішкових елементів можуть бути реалізовані лише за умови використання в якості вихідних компонентів металів високої чистоти та застосування нових технологій їх отримання.