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Present status and future prospect of the Russian program for fusion low-activation materials

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Abstract

The Russian Fusion Materials Program (1998–2000, Minatom of Russia) includes the study of low (reduced)-activation V–Ti–Cr alloys, heat-resistant ferritic–martensitic steels and beryllium. The focus of the vanadium alloy program is on the high purity and homogeneity of V–(4–20)Ti–(4–10)Cr ingots (30–50 kg). The main compositions are V–(8–10)Ti–(4–5)Cr and V–4Ti–4Cr alloys. The focus of the steel program is on 10–12% Cr heat-resistant reduced-activation ferritic–martensitic steels (RAFMS). The focus of the beryllium program is on increasing production scale, decreasing impurity concentrations (decreasing of activation level), and new materials development, such as porous (15–30% open porosity) Be and new grades of Be.

1. Introduction

The requirements to ensure safety of future fusion reactors are increasing, and from this point of view, the development of low (reduced)-activation materials (structural, protective, breeding) is relevant. The concept of the Russian design of a fusion reactor (DEMO-RF) includes the use of low-activation materials, with a possibility for their post-reactor recycle within acceptable time limits (less than 100 yr after the reactor is shut down) and a minimization of ecological problems that arise from reactor operation [1,2]. The choice and development of well-defined low-activation materials suitable for construction are a complex problem and depend on reactor operating conditions along with the additional requirement of a reserve of high-temperature serviceability of the materials (approximately 100°C above working temperatures). In Russia (SSC RF-VNIINM, industry), the following materials for fusion reactors are being developed [2–5]:

1. low-activation structural alloys of the V–(4–20)Ti–(4–15)Cr system with working temperatures up to 750°C;
2. heat-resistant, reduced-activation ferritic–martensitic 10–12% Cr steels (RAFMS) with working temperatures in the range 300–650°C;
3. beryllium as a protective (at temperatures 140–700°C) or breeder (at temperatures 500–700°C) material.

2. Radiation trials of materials

Development of promising radiation-resistant materials requires testing in radiation facilities of different types. At present such radiation facilities in Russia are the BR-10, BOR-60 and BN-600 fast reactors (Fig. 1) and the IVV-2M thermal reactor. To calculate activation and transmutation processes in the materials during neutron irradiation in these various spectra, an elaborate database of nuclear data has been developed for the base, alloying and impurity elements. The specialized libraries of activation cross-sections FENDL/A-2.0, the decay data FENDL/D-2.0 and the program FISPACT-4

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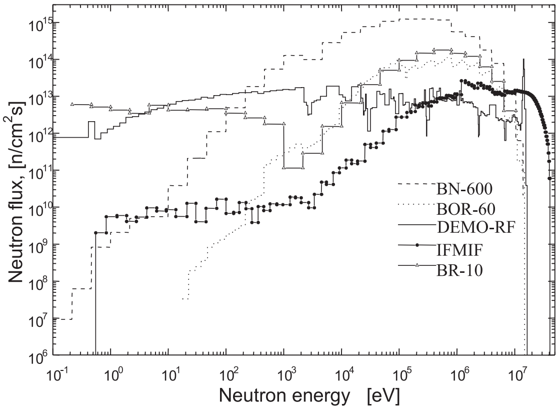

Fig. 1. Neutron spectra of BN-600, BOR-60 and BR-10 fast reactors, DEMO-RF fusion reactor (self-cooling V–Ti–Cr liquid lithium blanket) and the neutron source IFMIF.

for calculation of transmutations and induced activity have served as the basis for this activity.

For fusion materials, intense and volumetric sources of 14 MeV neutrons (accelerator and plasma-based sources) are being developed. The most advanced project is the international fusion materials irradiation facility (IFMIF), developed by the IEA on the basis of two deuteron accelerators with deuteron energy 30–40 MeV and current 2 × 125 μA [6]. Correlation of radiation effects on materials in the IFMIF neutron spectrum (Fig. 1) with those from fission and fusion reactors requires further investigation to derive and improve the nuclear data for high-energy neutrons (14–50 MeV) and the effect of such neutrons on materials and their properties. In Russia (Budker Institute of Nuclear Physics, Novosibirsk; Institute of Technical Physics, Snezhinsk), a volumetric and intensive D–T-plasma-based 14 MeV neutron source is being designed on the basis of a gas dynamic trap (GDT-NS) [7–9]. The IFMIF and GDT-NS should provide favorable conditions for fusion materials irradiation testing.

3. Low-activation alloys V–Ti–Cr

At present the SSC RF-VNIINM, jointly with the Russian industry, is conducting investigations to select and optimize compositions of alloys in the V–(4–20)Ti–(4–15)Cr system and to develop industrial metallurgical and manufacturing processes for obtaining alloys and products [2]. The main efforts are focused on obtaining V–4Ti–4Cr and V–(8–10)Ti–(4–5)Cr alloys of high purity (Table 1) and homogeneity with heats up to 30–50 kg.

For the compositions V–4Ti–4Cr and V–10Ti–5Cr (Table 1), the induced activity, nuclear transmutation of isotopes, and the time-dependent activity after reactor shutdown have been calculated for several reactors for a fluence of 5×10^{27} n/m^2. The neutron spectra of the reactors and the level of impurities in the alloys determine their activation properties, as well as the time to reach a remote level of activity (10^{-2} Sv/h) after reactor shutdown. Without impurity reduction, this time is long: 20–25 yr (BOR-60); 45–55 yr (BN-600); 60–80 yr (DEMO-RF). The radiation production of hydrogen and helium is significant and also depend on neutron spectra (Fig. 2).

Reactor trials of the Russian alloys V–4Ti–4Cr and V–10Ti–5Cr are planned for 2001–2003 in BN-600 to a dose of 60–80 dpa and at irradiation temperatures 400–750°C in stationary lithium.

3.1. Electric-insulating coatings of alloys V–Ti–Cr

When using alloys for commercial thermonuclear reactors with magnetic confinement and a lithium coolant, methods and technologies for obtaining electrically insulating, self-healing coatings on materials are required [10–12]. Investigations are being conducted on AlN-base (high-temperature technology, 700–800°C) and CaO-base (low-temperature technology, 350–

Table 1
Chemical composition of advanced V–Ti–Cr alloys

Element	Compositions, wt% (max impurity level)	
	V–4Ti–4Cr (50–300 kg)	V–10Ti–5Cr (50–300 kg)
V	Basis	Basis
Cr	4 ± 0.5	5 ± 0.5
Ti	4 ± 0.5	10 ± 0.5
Si	0.025	0.025
O	<0.040	<0.040
N	<0.015	<0.015
C	<0.020	<0.020
H	<0.001	<0.001
Al	<0.020	<0.020
Fe	<0.025	<0.025
Cu	<0.010	<0.010
Mo	<0.01	<0.01
Nb	<0.005	<0.005
Cl	<0.0003	<0.0003
Ga	<0.0010	<0.0010
Ca	<0.0001	<0.0001
Na	<0.0001	<0.0001
K	<0.0001	<0.0001
Mg	0.0001	<0.0001
P	<0.002	<0.002
S	0.002	0.002
B	<0.0005	<0.0005
Ag	<0.0001	<0.0001
Co	<0.0005	<0.0005
Ni	<0.001	<0.001

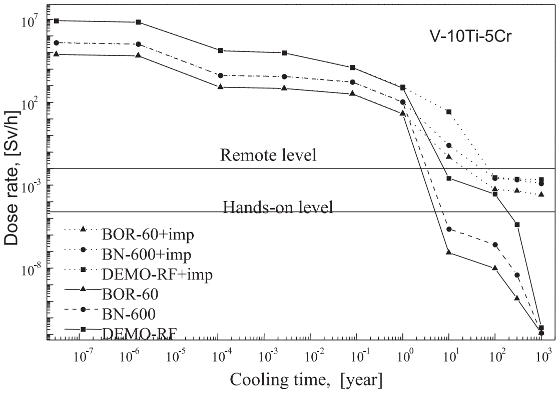

Fig. 2. Time-dependent dose rate of V–10Ti–5Cr alloys with and without impurities after shutdown of BOR-60, BN-600 and DEMO-RF reactors (total fluence 5×10^{27} n/m^2 for the reactor).

450°C) coatings. AlN-base coatings have good functional properties, but production is very difficult because of the high temperatures needed for formation and self-healing. Formation of such coatings requires a particular level of nitrogen concentration in lithium, which also imposes a number of demands on the composition of the V–Ti–Cr alloy. For such coatings an alloy of composition V–(8–10)Ti–(4–5)Cr has the best properties from the standpoint of resistance to corrosion and stability of the nitride layer formed in lithium with variable concentrations of nitrogen and for the realization of technologies for making protective nitride coatings [2,12].

CaO-base coatings are produced by low-temperature processes (compared to AlN), and high-temperature properties of such coatings require further examination. Moreover, the supply of oxygen from an alloy to the coatings is indispensable for the formation and subsequent self-healing of such a coating, and this creates major problems for making an alloy and product forms with a large oxygen content. Further investigations are necessary to select the ultimate composition of a V–Ti–Cr alloy compatible with electrically insulating CaO-based coatings.

4. Reduced-activation ferritic–martensitic 10–12% Cr steels

The necessity of developing heat-resistant steels is dictated by the high-working temperatures of a fusion reactor blanket (600–650°C), and also by the softening of steels of the ferritic–martensitic class at long operation (irradiation more than 100 dpa) at high temperatures. To provide high resistance to low-temperature radiation embrittlement, the microstructure of the steel should have a minimum content of δ-ferrite and impurities that contribute to embrittlement (gaseous species and low-melting metals). Such a microstructure and composition should be ensured by the technology of fabrication (vacuum melt and remelt, optimization of the technology operations, etc.) [4].

Now in Russia (SSC RF-VNIINM, industry), the following RAFMS are being developed and investigated:

Fe–(10–12)Cr–(1.00–2.00)W–0.01Mo–(0.30–0.50)Si
–(0.20–0.40)V–0.01Nb–(0.5–0.8)Ti–(0.20–2.00)Mn
–(0.003–0.006)B–(0.10–0.20)C–(0.05–0.10)N
–0.01O–0.10Al–0.005P–0.005S–0.01Co
–(0.01–0.50)Ni–(0.01–0.10)Cu–0.01Ag–0.10Ce
–(0.10–0.20)Ta

Activation and transmutation of these steels for the range of impurity concentrations (min and max and have been calculated for the neutron spectra of reactors DEMO-RF and BOR-60 for a fluence of 5×10^{27} n/m^2), as shown in Fig. 3. These results provide an opportunity to evaluate adjustments in the composition and technology of steel making to reduce the level of residual activity after reactor shutdown. It is necessary to note that during irradiation (DEMO-RF), the concentrations of some elements (C, N, O, P, S, etc.) do not change, whereas the concentrations of other elements (Li, Sn, Zn, Mg, Ca, etc.) increase to amounts sufficient to influence the functional properties of the material. The final composition and impurity level result in decay times to reach a residual activity of 10^{-2} Sv/h of 20 yr for BOR-60 and 60 yr for DEMO-RF).

Further development of this class of materials requires:

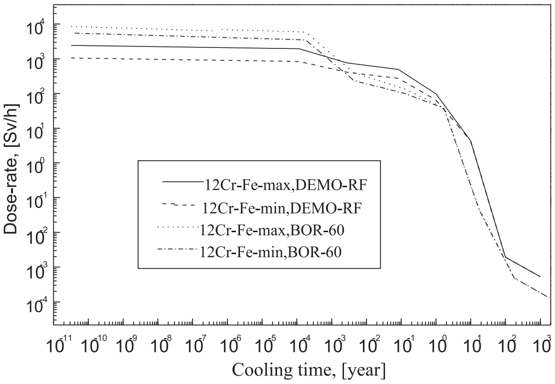

Fig. 3. Time-dependent dose rate of two types of the 12Cr–RAFMS irradiated in BOR-60 and DEMO-RF reactors after shutdown (total neutron fluences 5×10^{27} n/m^2). The min/max corresponds to the minimum/maximum concentration of elements in the RAFMS (item 4).

1. better impurity control using high-quality initial charge materials and vacuum methods for melting and remelting;
2. optimization of heat-treatments and targeted irradiations of materials in prototypic irradiation conditions, including anticipated coolants and with cyclic thermal histories;
3. expansion of the temperature range of irradiations towards both low (200–350°C) and elevated (450–650°C) temperatures.

At present in Russia (SSC RF-VNIINM, industry), a number of experimental heats and one industrial heat (11% Cr) of RAFMS have been obtained. All preparations for melting the steels were made to minimize the content of the deleterious elements mentioned above. The compositions of the steels are now being analyzed, and their initial physical and engineering properties will be explored. Irradiation of these steels is planned in BOR-60 and BN-600 in 2000–2003 to 10–80 dpa at irradiation temperatures in the range 340–600°C in a flowing sodium environment.

5. Beryllium

SSC RF-VNIINM is developing compact, porous and granulated beryllium [2,13,14]. Depending on the anticipated application, beryllium fabrication and impurity content can be varied (97.4–99.4 wt% Be).

The basic requirements of beryllium are:

1. high-dimensional stability and sufficient strength under neutron irradiation at temperatures up to 750°C;
2. low activation under irradiation, which is determined by purity and neutron spectrum;
3. the production of components on an industrial scale.

In SSC RF-VNIINM beryllium with strength in the range 600–700 MPa at room temperature and strength in the range 180–220 MPa at 650°C has been obtained. However, to obtain acceptable times to achieve remote levels of residual activity after shutdown, further work is required to diminish impurity concentration from their current levels. Fig. 4 shows that for customary industrial beryllium (98%), the time to reach a level of 10^{-2} Sv/h after one-year irradiation is 15–20 yr (BOR-60, BN-600) and 40 yr (DEMO-RF).

A high-temperature-resistant grade (DSHG-200) and a radiation-resistant grade of beryllium (TR-30) have been designed and obtained in pilot-industrial amounts. These grades have been recommended as prospective shielding materials for fusion reactors, including ITER. Long-time (1000 h) annealing of these materials has shown good thermal stability of their mechanical properties and structures [2,5,14]. Irradiation experiments on TR-30 have shown that, despite a considerable drop in strength, after irradiation at 750°C up to a fluence of 2.4×10^{25} m^{-2} by fast neutrons the residual strength is at a level characteristic of the majority of industrial grades in the unirradiated state.

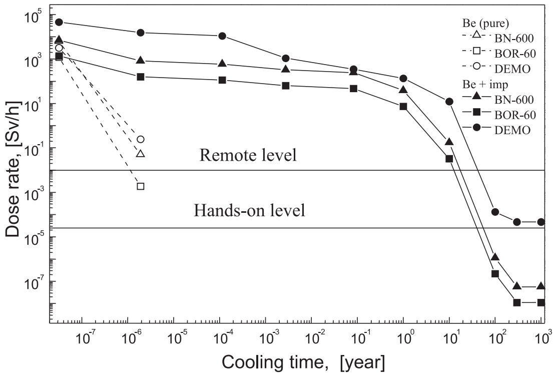

Fig. 4. Time-dependent dose rate of pure and impure (98.0%) beryllium after one-year irradiation in neutron spectra of reactors BN-600, BOR-60 and DEMO-RF (Fig. 1).

Experimental tritium-production modules of DEMO have been designed and manufactured in Russia [1,2]. The important requirements for the beryllium breeder are:

1. a fully open porosity at a level of 15–30% for free removal of radiogenic gases;
2. a maximum heat transfer (good contact) between beryllium and the steel shell.

At present two models of the breeding zone of the DEMO reactor have been manufactured [2,13]:

1. a model employing lithium orthosilicate and porous beryllium (open porosity 21.9%);
2. a model employing lithium orthosilicate and granulated beryllium, with two sizes (1.2–2.5 and 0.2–0.3 mm) to obtain a filling density of 78%.

Ferritic–martensitic steel EP-450 (12Cr–2Mo–Nb–V–B) with a protective coating of alumina has been chosen as the construction material for these models at this stage. The models have been installed for reactor trials in the channel of the IVV-2M thermal reactor.

5.1. Granulated beryllium

For comparison of beryllium of different types in SSC RF-VNIINM [2,5,13], a testing technique has been developed for a beryllium breeder of the filling type with a filling density of 78–80%. Filling from two particle size fractions, for example 1.5–2.5 and 0.2–0.3 mm, is necessary to achieve the desired density of beryllium. However, low thermal conductivity and absence of continuity of contact of granulated beryllium with the interior surface of the tube hamper effective operation of a beryllium breeder. These problems are absent when beryllium with open porosity is used.

5.2. Beryllium with open porosity

With technologies developed in SSC RF-VNIINM [2,5,13], it is possible to obtain porous beryllium in a steel tube with a dense contact between the porous beryllium and the steel tubes. The beryllium with an open porosity of 15–30% is a promising material for a breeding blanket. In mechanical tests, beryllium with open porosity behaves similar to a sintered material. There is a good correlation between the properties of porous beryllium and the amount of open porosity. The coefficient of thermal expansion for porous beryllium is similar to that of compact beryllium. The thermal conductivity of porous beryllium exceeds by 10–15 times the corresponding value for a dual particle size compact of identical density.

5.3. Pilot production of beryllium in Russia

Basic pilot-production efforts on the development of beryllium and beryllium product forms are aimed at:

1. fabrication and examination of functional properties of compact, porous and granulated beryllium, while decreasing the manufacturing cost and reducing impurity concentrations to reduce residual activity;
2. determining the effects of neutron and gamma spectra on activation and transmutation;
3. supply of beryllium products (compact, porous and granulated) for research and development and engineering, including ITER and DEMO designs.

The program can presently provide:

1. production of compact metal beryllium and product forms;
2. recycling beryllium (scrap of used articles);
3. production of porous beryllium (adjustable open porosity 15–30%) and product forms, including inside tubes of a complex shape with a dense contact between beryllium and the interior surface of the tube;
4. production of granulated beryllium with different particle size fractions.

6. Conclusion

1. Materials science and technological capablities of Russia can be used to produce V–(4–20)Ti–(4–10)Cr alloys, ferritic–martensitic 10–12% Cr steels and beryllium as well as product forms in sufficient amounts for research and development and engineering applications, including ITER and DEMO.
2. Further irradiation tests of fusion materials are planned for fluences 30–80 dpa and irradiation temperatures 380–750°C in 2000–2003. For such purposes the fast reactors BOR-60 and BN-600 will be used.
3. An intense, volumetric D–T-plasma-based source of 14 MeV neutrons is being designed on the basis of the GDT-NS.
4. Realizations of intense 14 MeV neutron sources (IFMIF, GDT-NS) would provide the much needed database for examination of materials for fusion reactors. The problem of using small specimens in such sources requires further investigation. In the case of the neutron source IFMIF, it is also necessary to extend/improve the nuclear database and to explore peculiarities of radiation damage of materials for high (14–50 MeV) energies of neutrons.

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