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UDC 669.182.2:621.365.2

DOI: <http://dx.doi.org/10.17580/cisr.2017.02.02>

IMPROVEMENT OF THE MELTING TECHNOLOGY AND LADLE TREATMENT OF STEELS 15X2HMΦA (15Kh2NMFA) (A-A, CLASS 1) FOR SPECIAL CRITICAL DUTY COMPONENTS IN NUCLEAR POWER STATIONS*

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ABSTRACT

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The ways of increase of the power engineering products resource for large-size critical components made of steel 15Kh2NMFA are described in terms of radiation and thermal brittleness criteria due to the content restriction of harmful and impurity elements, primarily phosphorus, sulfur and hydrogen. The steelmaking process for this steel grade includes smelting of liquid semiproduct in the electric arc furnace DSP-120, secondary refining process and ladle-vacuum treatment. The main technological task in melting of this semiproduct is obtaining of a final phosphorus content not more than 0.003% using deep dephosphorization process. For this purpose solid carburizers in the charge, such as pig iron and coke, are replaced by pulverized carbon-containing materials, blowing-in with oxygen or adding to slag during oxidizing period. In order to organize the process of deep desulfurization simultaneously with the removal of hydrogen, it is necessary to obtain the optimal slag composition in the required amount and high deoxidation of the metal before ladle vacuum treatment. Deep bulk deoxidation was carried out immediately during discharge of liquid semiproduct out of the electric arc furnace. Regulated content of the following elements was obtained as a result of usage of these methods: phosphorus 0.003–0.004%, sulfur 0.001–0.002%, hydrogen 0.8–1.1 ppm, oxygen activity 3–5 ppm.

Key words:

heat-resistant steels, melting, liquid semiproduct, dephosphorization, desulfurization, deoxidation, vacuum treatment, charge materials.

1. Introduction

Rise of efficiency and safety of nuclear power engineering require increase of service life of nuclear power plants (NPP) and level of their reliability. It concerns to

the shells of nuclear reactors (NR) in the most degree because just they determine the resource of nuclear power plants in general [1–3]. It also stands the new requirements to the materials for large shell products. NR shells are large and complexly loaded products and shell materials are subjected during operation to mechanical loading at high temperatures as well to thermal and radiation (for NR shell) embrittlement [4–10]. Resource of shells is determined by saving of the required level of tough–ductile properties, what requires rise of their initial level as well

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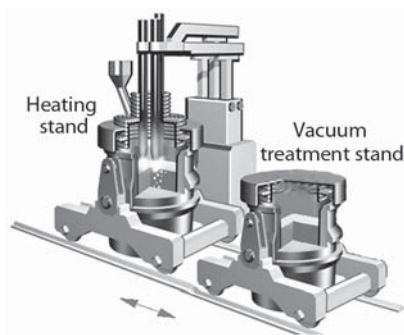


Fig. 1. Ladle refining and vacuum treatment unit UVRV-1 (ASEA SKF)

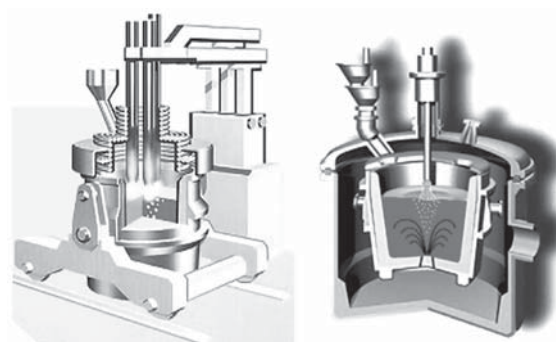


Fig. 2. Ladle refining and vacuum treatment unit UVRV-3 (LF, VD/VOD)

as decrease of their degradation rate during operation. These tasks can be solved both due to development of the new shell materials and to improvement of the complex of properties of the existing ones. In this case restriction of content of harmful elements and impurities (first of all — phosphorus, sulfur and hydrogen) is one of the most efficient methods for increase of shell service life based on the criteria of radiation and thermal embrittlement.

2. Problem setting

The manufacturing technology for 15X2HMΦA (15Kh2NMFA) (A–A, class 1) steels used for nuclear reactors (see **tab. 1**) include melting of a liquid semiproduct in electric arc furnace DSP–120 and its finishing in the ladle refining and vacuum treatment units UVRV–1 and UVRV–3 (**fig. 1** and **fig. 2**).

It was required to conduct the following investigations.

1. Manufacture of liquid semiproduct in the electric arc furnace to provide the required content of harmful impurities.
2. Development of the technology of finalizing of liquid steel during ladle treatment to provide the required parameters of liquid metal before casting, i.e. to provide the chemical composition.
3. Research of dephosphorization, desulphurization and degassing of 15X2HMΦA (15Kh2NMFA) (A–A, class 1) steels used for nuclear reactors.

3. Description of investigation

Investigation of the technology aimed in improvement of metallurgical quality has been conducted in the conditions of “OMZ (United Machine–building Works) Spetsstal” enterprise, at the electric arc furnace DSP–120 and in the ladle refining and vacuum treatment. The main technological problem in melting of a liquid semiproduct is conduct-

ing of the process of deep dephosphorization and obtaining of final phosphorus content not more than 0.003%. Large number of works [11–14] has been devoted to investigation of this process, but the final phosphorus content in these researches made usually 0.010–0.015%. Thereby it was necessary to pay special attention in the investigations of melting technology of extra low–phosphorus steels to the parameters determining deepness of dephosphorization process, such as basicity, oxidation and amount of slag.

Considering the ladle treatment, it should be underlined that the company “Izhorskie zavody” (now “OMZ Spetsstal”) was a pioneer in mastering of ladle treatment technology on the equipment delivered by ASEA and SKF companies in 1980–ies. This technology was developed taking into account the existing equipment at that time.

4. Obtained results and their analysis

Modernization of the technology for liquid semiproduct melting in the electric arc furnace DSP–120 concerned both the composition of charge materials and directly the method of process implementation. Solid carburizers in charge material, such as iron and coke, were replaced by pulverized carbon–containing materials (such as UМVK, USM) that are blowing in the furnace together with oxygen or adding to slag during oxidizing period. The amount of carbon–containing materials is in the range 5–20 kg/t. their feed rate makes 20–30 kg/min and oxygen consumption varies up to 30 m³ (see **tab. 2, a**).

Dosed injection of pulverized materials on the boundary of “metal — slag” separation provides optimal oxidation and basicity of slag. Slag basicity for CaO/SiO₂ compound makes ~ 4–5 units, while oxidation is equal to 16–23% (see **tab. 2, b**). It should be underlined for comparison that excessive slag oxidation (up to 50% FeO)

Table 1. Chemical composition of 15X2HMΦA (15Kh2NMFA) (A–A, class 1) steels used for nuclear reactors														
Steel grade	Elements, % (mass.)													
	C	Si	Mn	Cr	Ni	Mo	V	Cu	S	P	As	Co	Sn	Sb
15Kh2NMFA	0.13–0.18	0.17–0.25	0.3–0.6	1.8–2.3	1.0–1.5	0.5–0.7	0.10–0.12	≤ 0.3	≤ 0.008	≤ 0.008	≤ 0.02	≤ 0.03	–	–
15Kh2NMFA–A								≤ 0.1	≤ 0.007	≤ 0.007	≤ 0.01		≤ 0.005	≤ 0.05
15Kh2NMFA class 1					1.0–1.3			≤ 0.06	≤ 0.005	≤ 0.006	≤ 0.01			

Table 2. Charge material, variations of metal (a) and slag (b) chemical composition in the electric arc furnace DSP–120

No. of melt Melt mass, t	Charge material, t				Fluxes, t						C	P	S	α_0	t_{OK} , min
	HBI	PCB ¹	Wastes	Al _k	Lime	SiSm4		UMVK15	UMVK25	USM–B					
					MKP	C1									
124446 149007 Yield 115.0 t Heel 14.0 t	89	43.8	16.0	0.207	— 4.0	3.0	2.0	1.5	1.0	1.0	0.11 0.035	0.005 0.003	0.038 0.027	— 0.0795	60'
124447 163005 Yield 115.0 t Heel 10.0 t	89.5	43.2	16.0 Болото –14.0	0.206	— 2.0	3.0	2.0	2.0	1.0	—	0.09 0.07	0.004 0.003	0.027 0.03	— 0.0393 [C]–0.06	60'
124448 Yield 113.0 t			Болото –10.0		— 2.8	3.0	—	— 0.5	— 0.7	—	0.05 0.07	0.003 0.003	0.02 0.022	— 0.025 [C]–0.09	30'
124488 89875 Heel 8.2 t			73.6	0.115	— 4.0	3.0	—	— 1.5	2.0 0.5	—	0.11 0.05	0.007 0.003	0.022 0.003	— 0.0375	60'

¹ Passport Charge Billet;
*— numerator: for melting; denominator: before tapping.

No. of melt	Chemical composition, %										
	Al ₂ O ₃	MgO	SiO ₂	P ₂ O ₅	S	CaO	TiO ₂	Cr ₂ O ₃	MnO	FeO	
124446	7.2	6.7	11.9	0.25	0.11	41.1	0.2	0.8	6.7	23.2	
124447	8.1	4.4	10.3	0.21	0.24	45.9	0.2	0.7	7.8	19.8	
124448	9.5	5.6	10.4	0.17	0.14	49.9	0.1	0.5	5.5	16.0	
124488	8.5	4.7	11.5	0.21	0.90	42.2	0.2	0.7	7.5	19.7	

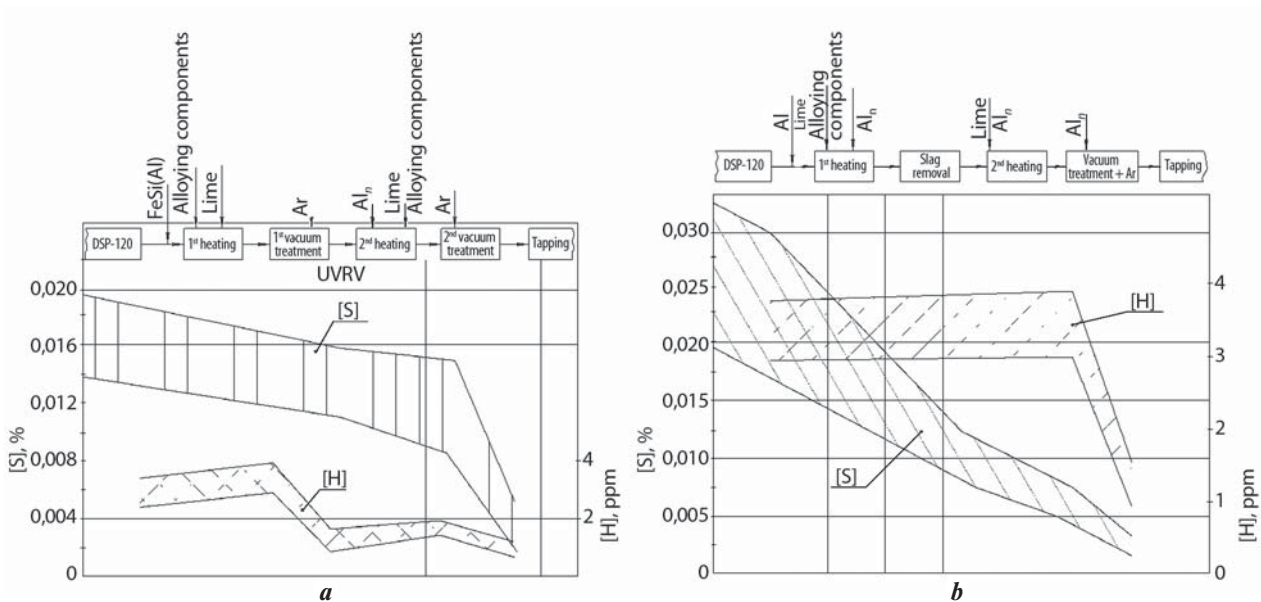


Fig. 3. Variation of hydrogen and sulfur content in the metal during ladle treatment with two (a) and one (b) vacuum periods

in the former, classic technology often has led to low slag basicity (less than 2.5 units).

Refuse of iron use in charge material allowed to decrease initial phosphorus content by 0.01%. Relatively low initial phosphorus content in charge material (~ 0.01–0.015%) and optimal slag composition made it possible to obtain phosphorus content just during melting at the level not more than 0.005–0.007% and to decrease it before tapping down to 0.003% (see tab. 2, a).

It should be mentioned that injection of large amount of carbon materials with sulfur content up to 0.8% leads to rise of sulfur concentration in a liquid semiproduct up to 0.020–0.038% (in addition to the positive effect).

Inauguration of oxidation control before tapping is considered as the important improvement of the melting technology for a liquid semiproduct in the electric arc furnace DSP–120. Measurements of oxygen activity in the melt allow to provide express analysis for de-

termination of carbon content and timely termination of oxidizing period without excessive over-oxidation of metal and slag and increased metal waste. In this case, when carbon content is restricted by 0.08–0.1%, oxygen activity was in the range 250–600 ppm (see table 2, a).

When we consider the process of ladle treatment, it should be reminded again that the company “Izhorskie zavody” (now “OMZ Spetsstal”) was a pioneer in mastering of ladle treatment technology on the equipment delivered by ASEA and SKF companies in 1980—ies based on the production facilities operated at that time. The process with double vacuum treatment has been developed and mastered for extra high-duty products (see fig. 3, a). The first vacuum period was used mainly for solving the problem of hydrogen removal and vacuum carbon deoxidation of metal and slag. Usage of this scheme was caused by the absence of reliable systems for bottom argon blowing of metal during the period of development of this technology. Thereby it was necessary to organize vacuum carbon “boiling” and hydrogen removal into floating carbon oxide bubbles to realize dehydration. It was shown (see fig. 4, a), that oxidation of ~ 0.02% of carbon during vacuum treatment is required for efficient hydrogen removal [15].

Appearance of the new argon blocks provided practically 100% guarantee of reliability of the blowing process. The conducted calculations displayed that argon consumption should make 3.0–4.0 m³ at [H₀] = 3.0–4.0 ppm and P_{ocr} = 1 mm Hg for efficient hydrogen removal from deoxidized metal in 100 t ladle down to 1.0 ppm (see fig. 4, b).

Multiple experimental data obtained during treatment of different steel grades have confirmed these results (see fig. 5). It can be seen that hydrogen content during vacuum treatment of deoxidized metal decrease (depending on the season) from 2.5–4.5 to 1.1–1.5 ppm. It was a prerequisite to transition to the ladle treatment route with one vacuum period, including steels for nuclear power stations (see fig. 3, b).

To organize the process of deep desulfurization together with hydrogen removal, it is necessary to provide the optimal slag composition in the required amount as well as high degree of metal deoxidation before vacuum treatment [16–19]. Previously developed technology envisaged step-by-step conducting of these processes with

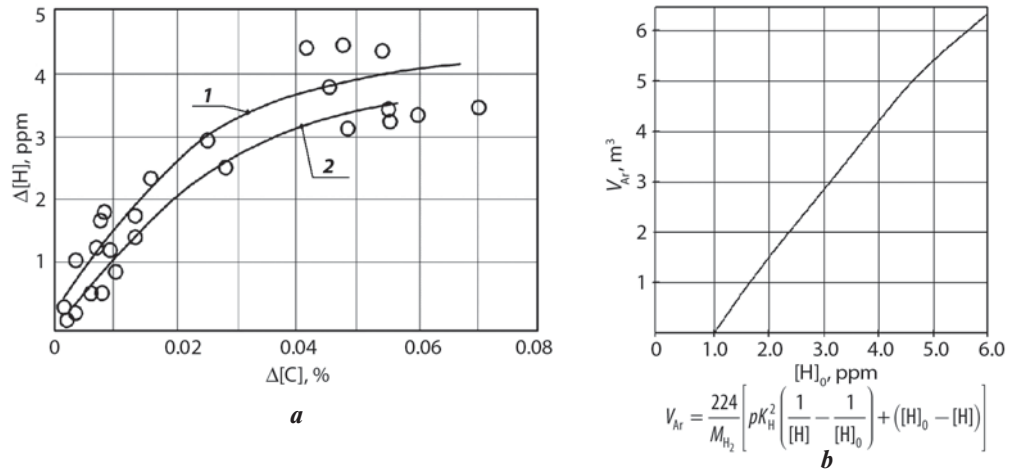


Fig. 4. Dependence of hydrogen amount removed during vacuum treatment on amount of eliminated carbon (a) and calculated relationship between minimal required argon amount to obtain final hydrogen content less than 1.0 ppm for different hydrogen initial content (metal mass is 100 t) (b):

1 — values of total amount of hydrogen removed from metal and slag; 2 — average values of amount of hydrogen removed from metal

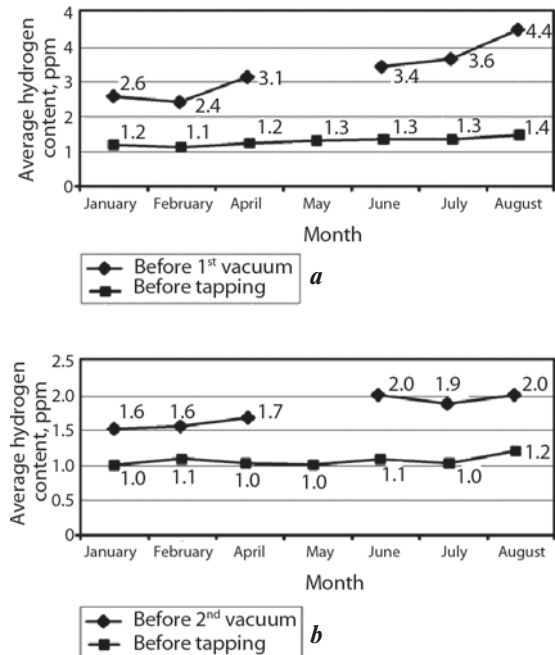


Fig. 5. Hydrogen removal via the technology with one vacuum treatment period for the metal deoxidized by aluminium (a) and with two vacuum treatment periods (b)

preliminary vacuum carbon and consequent deposited and diffusion deoxidation [20].

In the modernized variant, deep deposited deoxidation is conducted just during tapping of liquid semiproduct out of the arc furnace (see fig. 3, b). Added amount of bulked and pulverized aluminium makes 2.0 kg/t (0.2%) and 1–3 kg/t. This amount should be sufficient not only for metal and slag deoxidation, but also for melt protection from secondary oxidation during tapping. As a result, it is possible to have completely deoxidized metal and slag already in the beginning of the treatment.

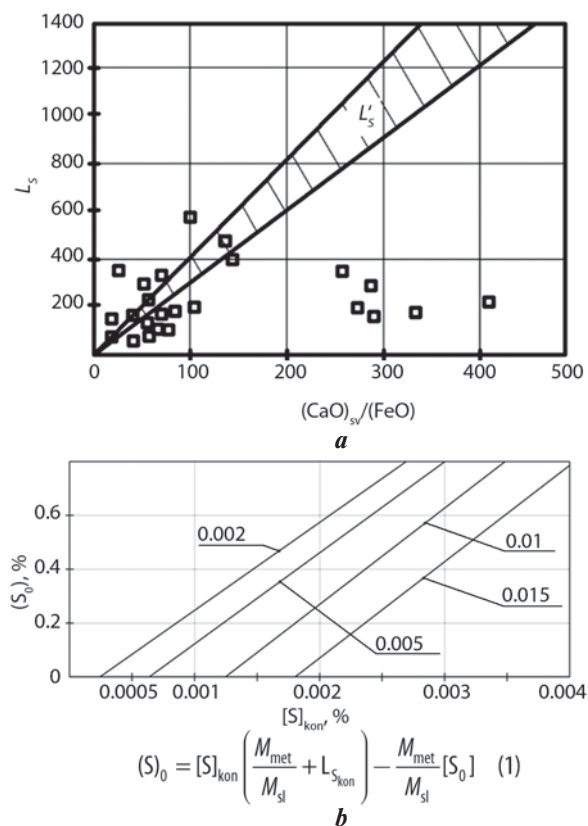


Fig. 6. Dependence between the sulfur distribution coefficient after vacuum treatment — equilateral relationship (a) and dependence between maximal allowable initial sulfur content in slag and initial sulfur content in metal (b) (numbers near graph lines mean initial sulfur concentration in metal)

Ladle treatment of the first four melts of 15Kh2NMFA (class 1) steels via the new technology was finalized in the following results. Aluminium content in the metal before vacuum treatment made 0.01–0.05% and content of Fe, Mn, Cr oxides in slag didn't exceed 0.3% for each of them. Slag basicity was in the range 4–12.

Solving the problem of dehydrogenization was not connected with any doubts, taking into account the accumulated experience. Metal blowing in vacuum conditions with argon (consumption 4.2–5.6 m³) provided its final content in the range 0.9–1.4 ppm.

It was more difficult to solve the problem of deep desulfurization, taking into account increased sulfur content (0.030–0.022%) and aim to obtain the final sulfur concentration not more than 0.002%.

In accordance with the developed technology of slag deoxidation and forming the liquid slag layer on metal surface, sulfur content in metal during ladle-to-ladle tapping and reheating decreased from 0.016–0.030% to 0.004–0.007%. At the same time its concentration in slag increased to 0.35–0.60%. The actual coefficient of sulfur distribution between metal and slag made 50–75 units. Its equilibrium values for the obtained and practically ideal slag composition achieve 300–1500 units (see fig. 6, a). It seems that large reserve of sulfide

capacity can be easily realized in the following powerful metal stirring during vacuum treatment with argon blowing. But practical experiments displayed that the average value of maximal actual values of the distribution coefficient after vacuum treatment made about 300 units.

Slag amount makes usually ~ 2.5% of metal weight. Taking into account this information, we can conclude that final sulfur concentration depends mainly on its initial content in metal and slag. Initial slag content in metal is a preset value. Thereby it is a real option to influence during ladle treatment on final sulfur content in metal via lowering of its content in slag by its renovation. The required maximal allowable sulfur content providing the aimed final sulfur concentration in metal is shown on the fig. 6, b. It can be seen that initial sulfur concentration in metal and slag should be not more than 0.0015% and 0.08% respectively, to provide the final sulfur content in metal equals to 0.002%. The mentioned sulfur content in slag corresponds to sulfur content in lime — the main slag-forming component.

To provide the final sulfur concentration 0.001%, the initial sulfur content in metal should be not more than 0.006% or 0.002%, when the initial sulfur content in slag is 0.08% or 0.26% respectively. And to achieve the final sulfur concentration in metal 0.0005%, the initial sulfur content in metal should be not more than 0.002% and its initial content in slag should not exceed 0.08%.

Taking into account the high initial sulfur content in metal (more than 0.015%), we can testify that partial or complete slag renovation is required in this case to achieve sulfur concentration 0.002%.

The first melts conducted with slag renovation have confirmed completely all calculated data. Slag renovation allowed to decrease its initial sulfur content from 0.6% to 0.35–0.18%. The process of deep desulfurization was successfully conducted due to consequent intensive metal and slag stirring in vacuum conditions.

Sulfur content 0.001% has been obtained for the first time for two melts, and sulfur content 0.002% — for two other melts (see tab. 3, a). Oxygen activity in metal before tapping made 3–6 ppm for aluminium content 0.007–0.015%.

The ingot with mass 335 t has been manufactured from three melts of 15Kh2NMFA (class 1) steel (see tab. 3, a). Tapping has been conducted in vacuum conditions using a tundish. The billet of elongated rim of the active part of VVER–1000 reactor shell for the Belarus nuclear power station has been manufactured from this ingot. Expertise of the billet metallurgical quality has shown that its microstructure meets the requirements of the technical conditions and such unallowable defects as cracks, flakes, laminations, shrinkage porosity were not revealed. The results of final control of contamination of the billet feeder part with non-metallic inclusions also confirmed correspondence with the requirements of technical regulations (see tab. 3, b).

5. Conclusions

The developed and tested new melting technology allows to meet completely up-to-date strict requirements for metal quality with perspective of their future elevation. It is possible to regulate phosphorus content at the level 0.003–0.004%, sulfur content – 0.001–0.002%, hydrogen content – 0.8–1.1 ppm and oxygen activity – 3–5 ppm. The developed technology provides manufacture of steel with extra cleanness for harmful elements and makes it possible to improve substantially the complex of properties of prospective shell materials, what will lead to rise of efficiency and safety of the nuclear power industry.

The study was financially supported by Ministry of Education and Science of the Russian Federation within the scope of accomplishment of the Federal Targeted Program “Investigations and innovations on priority development directions of the RF scientific–technological complex for 2014–2020 (application code “2015–14–579–0173–366”). Agreement of subsidizing No. 14.578.21.0114 dated October 27, 2015. Unique identifier of applied scientific researches and experimental development (PNIER) — RFMEFI57815X0114.

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Table 3. Final content of harmful impurities, hydrogen, oxygen and aluminium in 15Kh2NMFA (A–A, class 1) steel, % (a) and the results of final control of contamination of the billet of nuclear reactor shell rim from the 335 t ingot (b)

(a)						
Steel grade	No. of melt	P, %	S, %	H, ppm	α_0 , ppm	Al, %
15Kh2NMFA–A class 1	188437	0.003	0.001	1.4	5.0	0.014
	197865	0.004	0.002	1.1	3.0	0.012
	100806	0.006	0.002	0.9	4.0	0.007

(b)						
	Sulfides	Spot oxides	Linear oxides	Brittle silicates	Ductile silicates	Non–deformed silicates
Final values (feeder part)	0.0	1.0	0.0	1.3	0.0	1.2
Requirements of technical regulations TU 0893–013–00212179–2003	2.5	2.5	2.5	3.5	3.5	3.5

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