NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 8(3): 219–223
DOI 10.3897/nucet.8.94540

Research Article

Experimental study of using microwave reflex-radar level gauges for liquid metal coolants*

Vladimir I. Melnikov[1], Tatiana A. Bokova[1], Vadim V. Ivanov[1], Aleksandr R. Marov[1], Natalia A. Lobaeva[1], Anatoly S. Kvashennikov[1], Pavel A. Bokov[1], Nikita S. Volkov[1]

1 *Nizhny Novgorod State Technical University n.a. R.E. Alekseev, 24 Minin Str., 603950 Nizhny Novgorod, Russia*

Corresponding author: Tatiana A. Bokova (tatabo@bk.ru)

Academic editor: Yury Kazansky ♦ **Received** 30 September 2021 ♦ **Accepted** 15 May 2022 ♦ **Published** 27 September 2022

Citation: Melnikov VI, Bokova TA, Ivanov VV, Marov AR, Lobaeva NA, Kvashennikov AS, Bokov PA, Volkov NS (2022) Experimental study of using microwave reflex-radar level gauges for liquid metal coolants. Nuclear Energy and Technology 8(3): 219–223. https://doi.org/10.3897/nucet.8.94540

Abstract

The article presents the results of work aimed at solving the problem of measuring the coolant level in miscellaneous tanks of liquid-metal-cooled reactor plants, mainly of an integral layout with a free level of the primary coolant. The choice of relevant measuring means and methods is limited by the extreme parameters of the liquid metal coolant (LMC) and operating conditions. Traditional measuring means are practically unsuitable; therefore, measuring the HLMC level is a complex technical task. Based on this review, they propose and describe a method of pulsed microwave reflectometry as the most promising in terms of combining the characteristics of reliability, accuracy and ease of use. The results of the experimental study demonstrated the efficiency of the level gauge, which worked according to this method, for measuring the level of lead-bismuth coolant in the control tank under conditions close to natural ones. An analysis of the results confirmed the possibility of using this method to control the level of melts of various metals as applied to HLMC reactor plants.

Using the device for measuring the level, which works according to the proposed method, it is possible to control the level of melt of various metals in tanks in real time without the need to move various parts of the sensitive element of the level gauge while maintaining the tightness of the circuit. This device is applicable for various nuclear power plants, accelerator-controlled systems, research reactors and experimental facilities with liquid metal coolants.

Keywords

Fast reactor, liquid metal coolant, coolant level, level measurement, level measurement methods

Introduction

Of all the currently existing power production technologies, nuclear power engineering is considered the most promising in terms of efficiency and environmental safety. Currently, heavy liquid metal coolants (HLMC), such as lead or lead-bismuth eutectic, are considered promising for the creation of reactor plants, since HLMC reactors meet passive safety requirements and have a higher efficiency compared to existing pressurized water nuclear power plants (NPPs) (Adamov et al. 2001).

Stable operation of NPPs is ensured by the systems of automatic control and monitoring of coolant parameters. A characteristic feature of HLMC reactor plants is

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2022, n. 1, pp. 79–89.

their integrated (tank) layout. These include the BREST, SVBR, BRS-GPG reactors (Adamov et al. 2001, Beznosov and Bokova 2011, Dzhangobekov et al. 2013, Beznosov et al. 2020a, b). The integral layout of the reactor is highly reliable and safe under external influences. The compact location of the core equipment, intermediate heat exchangers and primary circuit pumps shortens the circulation path of the primary coolant, reduces its hydraulic resistance, which leads to improved conditions for the development of natural circulation in the primary circuit when the plant is completely de-energized.

Statement of the problem and a review of the coolant level measuring methods

The tank layout implies a free level of the coolant, which must be constantly monitored and maintained within the specified range. The choice of means and methods for measuring the level of a liquid metal coolant is limited by its extreme parameters and operating conditions. Traditional measuring means are practically unsuitable; therefore, measuring the level of TLMT is a complex technical task.

The most important properties and operating conditions of a HLMC reactor plant, which should be taken into account in the first place, include a wide temperature range (200–550 °C) and high corrosive activity of the coolant with respect to structural materials, as well as uneven temperature fields in various parts of the plant, the need to create protective oxide coatings on the surfaces of structures, the presence of gas mixtures (inert gas, hydrogen, oxygen) in the gas cushions of the tanks and dissolved in the coolant, and, finally, the mandatory provision of the circuit leaktight integrity (Chirkin 1968, Chechetkin 1971, Beznosov et al. 2007).

The literature sources provide comparative characteristics of methods for measuring the level of various media, in particular depending on their physicochemical properties (Methods for Measuring). However, in open sources, there is practically no analysis of methods for monitoring the level of liquid metals, taking into account the operating conditions in NPPs and their physical properties.

At present, the most common means of level control in bench experimental circuits is an electro-contact level indicator. The principle of its operation is to register the closing of the circuit "power element – key – signal lamp" when a metal rod moving in height comes into contact with the surface of the coolant. The rod moves in an insulating seal. As a rule, simple fluoroplastic sealants are used, which are short-lived and need to be replaced frequently. At the same time, a violation of the general leak tightness of the gas circuit leads to an uncontrolled supply of oxygen with air, which causes uncontrolled oxidation of the coolant. And this, in turn, leads to the formation of solid oxides and clogging of the flow sections of the circulation circuit, partial or complete destruction of the flow part of the pumps, disruption of heat removal from the core, and other negative consequences.

To control the level of metal melts, it is customary to use multipoint signaling devices based on compact inductive transducers and inductive level gauges (Leshkov and Taranin 2008, Taranin 2015), as well as potentiometric devices operating on the principle of measuring the resistance of a tubular probe immersed in metal (Trakhtenberg and Deniskin 1967). Most of these developments were carried out decades ago, and are characterized by extremely high cost and low reliability (Kirillov et al. 1960).

Pulse microwave reflectometry and reflex-radar level gauge

To measure the level of a liquid metal coolant, it is proposed to use the method of pulsed microwave reflectometry. We present the design of the level gauge and the results of the study confirming its performance in the HLMC environment.

The method of microwave reflectometry is well known in measurement technology. In particular, it is used to locate faults in coaxial communication cables (Vorontsov and Frolov 1985, Tarasov 2005), to control the level of petroleum products (Needle and Shepard 1998, Melnikov et al. 2017, Manualslib 2021), and it has also been proposed to use it to control the water coolant of a nuclear power plant (Melnikov et al. 2018). The advantage of this method is the continuous measurement of the level of any media and the use even under the most difficult process conditions; operation of the device according to this method makes it possible to ensure the necessary leak tightness of the unit and the reactor plant as a whole, since there are no moving parts in the measuring probe (Fig. 1).

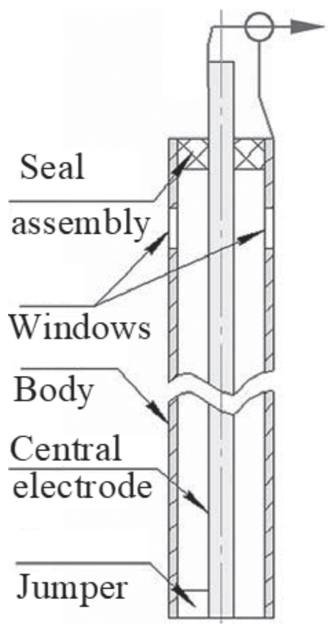

Figure 1. Structural scheme of the measuring probe.

The principle of operation of a reflex radar level gauge is based on the use of high-frequency electromagnetic energy pulses transmitted through a measuring probe partially immersed in a controlled liquid. The probe is a tube inside which an electrode is installed coaxially in the center.

The secondary equipment generates microwave pulses supplied at the top of the probe and measures the time delay of their passage to the surface of the controlled medium and back. If the level of the controlled medium in the tank increases, then the distance to the top of the probe and, accordingly, the time delay decrease proportionally. In an ideal system, this dependence is linear. The physics of the process is described in more detail in (Vorontsov and Frolov 1985, Tarasov 2005, Trenkal and Loshchilov 2016, Melnikov et al. 2017).

Thus, the level gauge consists of a measuring probe made in the form of a coaxial line (see Fig. 1), a communication line and a secondary electronic unit.

The probe body is made of a steel pipe with a diameter of 42 mm and a length of 1.35 m. A tube with a diameter of 10 mm, sealed on both sides, is used as the central electrode. The probe body and the central electrode at the free end are connected by a jumper, forming a short-circuited line. The controlled coolant freely fills the space between the pipes according to the principle of communicating vessels; for this, windows are provided in the upper part of the probe body. Electrical isolation and alignment of the central electrode in the upper part of the probe is made of PTFE. The wave impedance of the probe is 75 Ohm. A coaxial cable with the same impedance is used as a communication line.

The electronic unit includes (1) a rectangular pulse generator connected via a terminating resistor and a delay line to the measuring probe of the level gauge, (2) a gated comparator, the second input of which is supplied with voltage from the voltage generator, (3) a “pulse duration – amplitude” converter, (4) an analog-to-digital converter and (5) an “amplitude – current” converter (Fig. 2, p. 8).

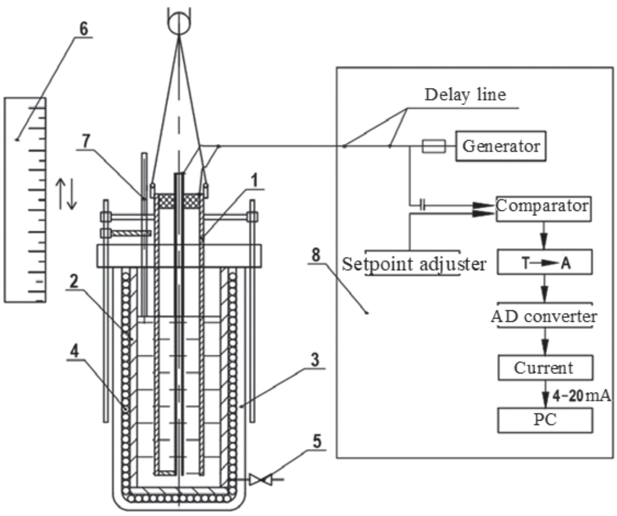

Figure 2. Scheme of the experimental installation: 1 – measuring probe; 2 – coolant control tank; 3 – thermal insulation; 4 – heating element; 5 – coolant drain valve; 6 – ruler; 7 –electro-contact signaling device; 8 – electronic unit.

The measuring system is controlled and data processed by a personal computer. The information is transmitted through the HART communicator via a two-wire line.

The generator uses an output stage based on a transistor with a cutoff frequency of 7 GHz, the rest of the circuit is based on a PIC series microprocessor.

The developed interface and software makes it possible to control the device operation during the measurement process. The view of the user page of the device for the operator is shown in Fig. 3.

Oscillograms of pulses at the probe outlet for two different values of the liquid level are shown in Fig. 4. It can be seen that the pulse duration decreases by about 6 ns with an increase in the level by 1 m. Considering that the resolution of the measuring circuit is about 50 ps, we obtain a level measurement step of about 1 cm.

Progress of the experiments and discussion of the results

The operation of the device was first tested under normal conditions in a water coolant. To do this, the control tank for the coolant was filled with water. The measuring probe of the device was immersed in water stepwise (with a step of 50 mm). The immersion depth was controlled with a ruler. The coolant level at each step of immersion (emersion) was controlled by an electro-contact (reference) level indicator. After each change in the immersion depth, the coolant level was measured by the reference and reflex-radar level gauges.

It was confirmed that the measured time delay and output current vary in proportion to the probe immersion depth in the liquid, in full accordance with previous studies of this method (Melnikov et al. 2017). The obtained data are shown in Figs. 5, 6. Fig. 6 shows quite satisfactory agreement between the liquid level recorded by the reflex-radar level gauge and the actual level.

After the operation of the device in the water coolant was tested, experiments were carried out using the lead-bismuth coolant. For this purpose, the control tank of the installation was filled with lead-bismuth melt, in which the measuring probe of the level gauge was placed. The temperature of the melt in the system gradually increased from 320 to 350 °C. At this temperature range, the first stage of the experiment was carried out on the lead-bismuth coolant.

Next, to determine the temperature effect on the level gauge performance, the second stage of the experiment was carried out at a melt temperature in the range of 420–450 °C.

When the experimental data on the lead-bismuth coolant at temperatures of 320–350 °C and 420–450 °C were compared, it was concluded that there was no significant temperature effect on the operation of this reflex-radar level gauge, since when two graphs for different temperatures were superimposed on each other, they practically

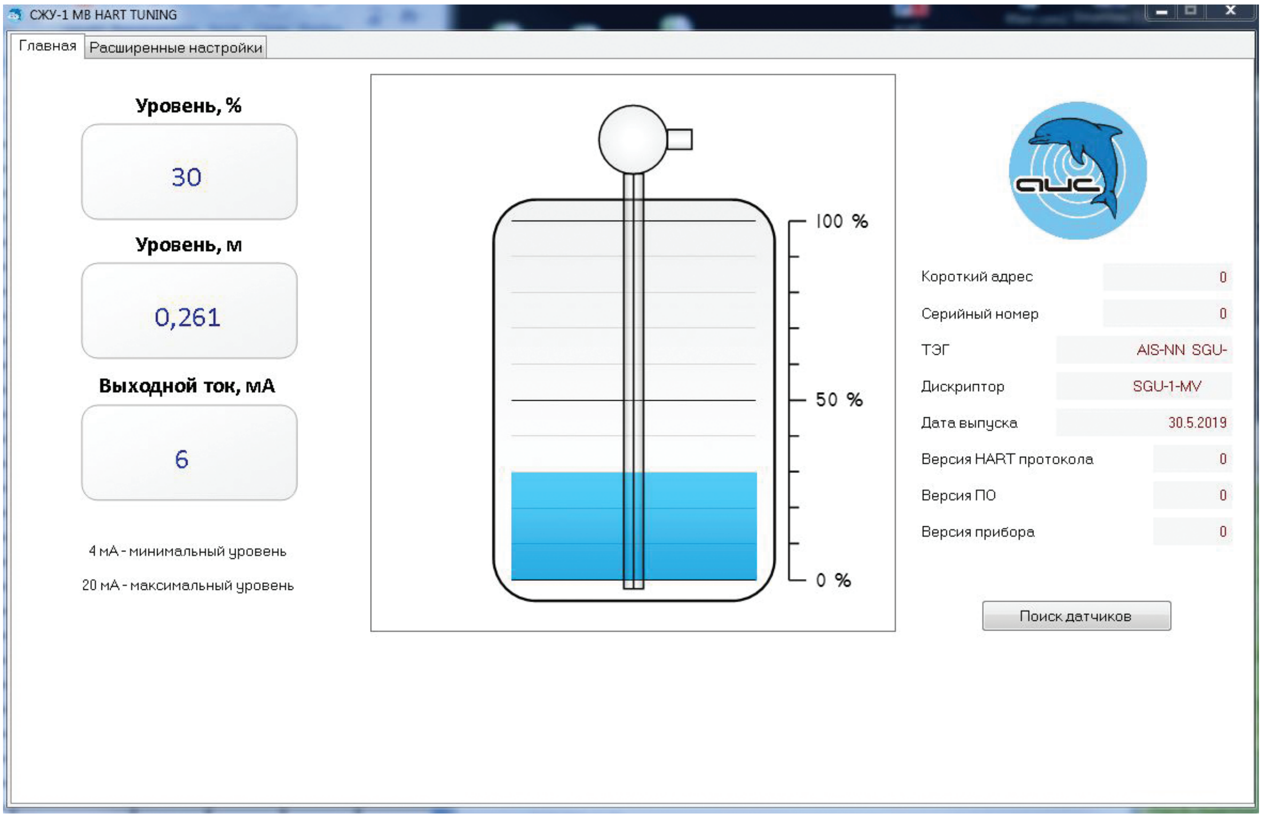

Figure 3. Screenshot of the main page of the level control device interface for the operator.

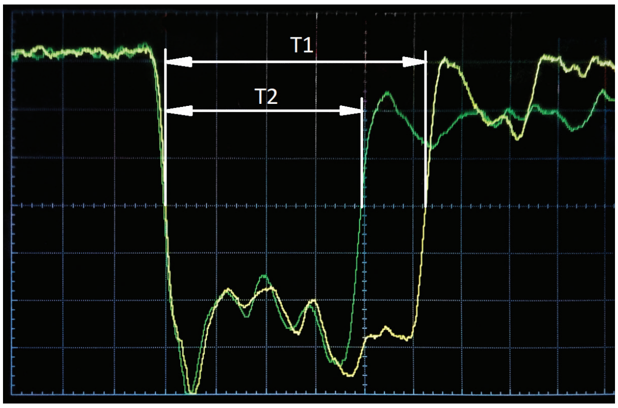

Figure 4. Oscillograms of signals at the output of the dried probe (T1) and immersed in the liquid to a depth of 1 m (T2). Scale: vert. – 0.2 V/cell; horizon. – 5 ns/cell.

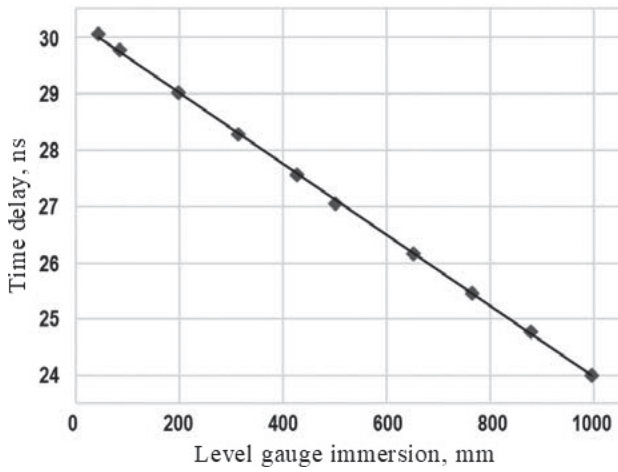

Figure 5. Dependence of the signal time delay on the probe immersion depth in the water coolant.

coincided. Therefore, the authors illustrated the confirmation of the operation of the level gauge only for the temperature range of 420– 450 °C (Figs 7, 8).

Note that, when the water level is measured at a minimum filling level (up to 50 mm), there is a nonlinear change in the output signals of the reflex radar level gauge from actual immersion in the liquid, which is due to the influence of the dielectric constant of water (Melnikov et al. 2018). It is necessary to take this fact into account when calibrating the instrument. At the same time, this phenomenon is not observed in the lead-bismuth coolant, since the signal is completely reflected from the metal surface even at minimal immersion.

The resulting discrepancy between the coolant level measured by the reflex-radar level gauge and the actual level is practically within a few millimeters, i.e. their quite satisfactory agreement is evident. The root-mean-square deviation of the measured level value from the actual one did not exceed 8 mm.

The experiment on the eutectic alloy was followed by a successful experiment on the water coolant in the same vessel. It can be concluded that the immersion of the reflex-radar level gauge in the lead-bismuth coolant did not affect its further performance in other media.

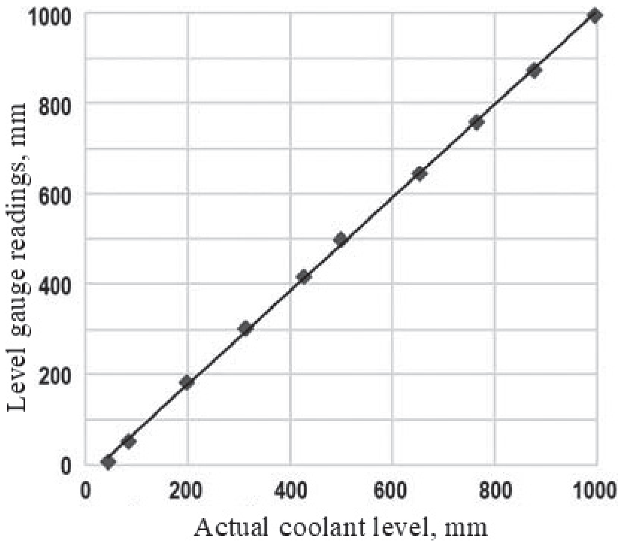

Figure 6. Comparative readings of the reflex-radar level gauge and the actual level of the water coolant.

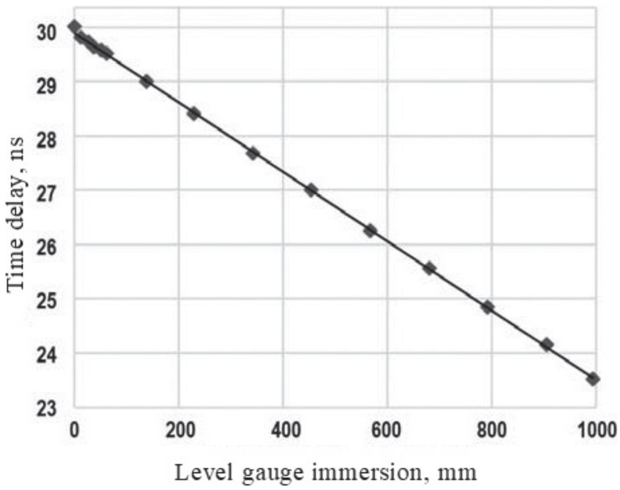

Figure 7. Dependence of the signal time delay on the probe immersion depth in the lead-bismuth coolant.

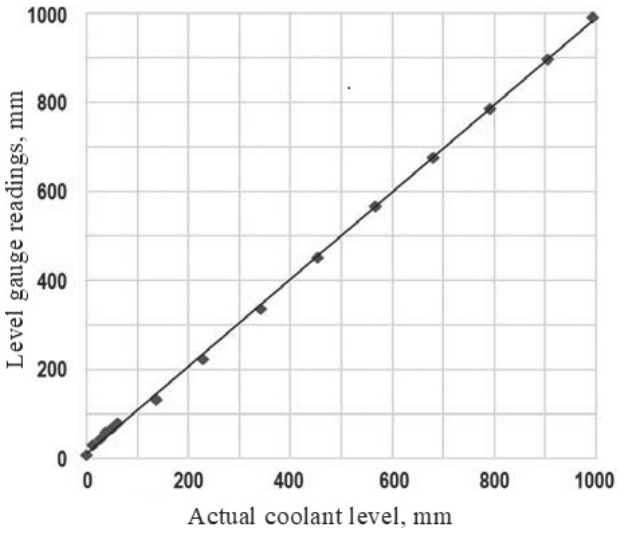

Figure 8. Comparative readings of the reflex-radar level gauge and the actual level of the liquid metal coolant.

At the end of the sensitive element of the level gauge at 50–75 mm after the experiments with the HLMC, the beginning of oxidation of its surface was observed, since this part of the sensor was in the metal for the longest time during the experiment. Subsequent tests tentatively showed no influence of the oxide film on the measurement results. However, this issue requires further research and resource testing.

Conclusion

The authors have experimentally confirmed the possibility of using the reflex-radar method to control the level of a liquid-metal coolant with reliable accuracy. Using the device for measuring the level, which works according to the proposed method, it is possible to control the level of melt of various metals in tanks in real time while maintaining the tightness of the circuit. This device is applicable for various nuclear power plants, accelerator-controlled systems, research reactors and experimental facilities with liquid metal coolants.

References

- Adamov EO, Bolshov LA, Ganev IKh, Zrodnikov AV, Kuznetsov AK, Lopatkin AV, Mastepanov AM, Orlov VV, Rachkov VI, Smirnov VS, Solonin MI, Uzhanova VV, Chernoplekov NA, Shatalov GE (2001) White Book of Nuclear Power. Moscow. GUP NIKIET Publisher, 269 pp. http://elib.biblioatom.ru/text/belaya-kniga-yadernoy-energetiki_2001/go,0/ [accessed Sep. 27, 2021] [in Russian]
- Beznosov AV, Bokova TA (2011) Equipment, layout and operation modes of circuits with heavy liquid metal coolants in nuclear power. Nizhny Novgorod. NGTU Publisher, 536 pp. [in Russian]
- Beznosov AV, Bokova TA, Bokov PA, Marov AR, Lvov AV, Volkov NS (2020a) Substantiation of Technical Solutions of the Reactor Circuit of the BRS-GPG Units of Small and Medium Power with a Heavy Liquid Metal Coolant for Ground and Floating NNPs. Trudy NGTU im. R.E. Alekseeva [Proceedings of NSTU n.a. R.E. Alekseev] 2(129): 64–76. [in Russian] https://doi.org/10.46960/1816-210X_2020_2_64
- Beznosov AV, Bokova TA, Bokov PA, Marov AR, Lvov AV, Volkov NS (2020b) Substantiation of Technical Solutions of the Reactor Circuit of the BRS-GPG Units of Small and Medium Power. VANT. Ser. Yaderno-Reaktornye Konstanty [VANT. Series: Nuclear Reactor Constants] 1: 132–139. [in Russian] https://doi.org/10.55176/2414-1038-2020-1-132-139
- Beznosov AV, Dragunov YuG, Rachkov VI (2007) Heavy liquid metal coolants in nuclear energy. IzdAT Publisher, Moscow, 432 pp. https://search.rsl.ru/ru/record/01003085239 [accessed Sep. 27, 2021] [in Russian]

- Chechetkin AV (1971) High temperature heat transfer fluids. Energiya Publisher, Moscow, 496 pp. [in Russian]
- Chirkin VS (1968) Thermophysical properties of materials in nuclear power. Atomizdat Publisher, Moscow, 484 pp. [in Russian]
- Dzhangobekov VV, Stepanov VS, Dedul AV, Klimov NN, Bolvanchikov SN, Vakhrushin MP (2013) Reactor Unit SVBR-100 for Modular Atomic Stations of Low and Medium Power. Proc. of the 4th Conference "Heavy Liquid Metal Coolants in Nuclear Technologies (HLMC-2013)", Sep. 23–26. IPPE JSC Publisher, Obninsk. http://www.gidropress.podolsk.ru/files/publication/publication2013/documents/245.pdf [accessed Sep. 27, 2021] [in Russian]
- ElectroTechInfo (2021) Methods for measuring and controlling the level. Types of level gauges. Comparison and Overview of Level Gauges. https://eti.su/articles/izmeritelnaya-tehnika/izmeritelnayatehnika_1521.html [accessed Sep. 27, 2021] [in Russian]
- Kirillov PL, Kolesnikov VD, Kuznetsov VA, Turchin NM (1960) Instruments for measuring pressure, flow and level for fused alkali metals. Atomnaya Energiya 9(3): 173–181. http://elib.biblioatom.ru/text/atomnaya-energiya_t9-3_1960/go,4/ [accessed Sep. 27, 2021] [in Russian]
- Leshkov VV, Taranin VD (2008) Inductive level gauge. Patent for Invention of the Russian Federation 2328704. No. 2006141311/28. Appl. 23/11/2006. Publ. 07/10/2008. [in Russian]
- Manualslib (2021) Instructions for installation and operation of the KROHNE BM100 Level Gauge. www.ste.ru/krohne/pdf/rus/russ_op_manualBM100.pdf [accessed Sep. 27, 2021] [in Russian]
- Melnikov VI, Ivanov VV, Teplyashin IA, Timonin MA (2017) Development and research of a Microwave Reflex-Radar Liquid Level Gauge. Datchiki i Sistemy [Gauges and Systems] 3: 50–54. [in Russian]
- Melnikov VI, Ivanov VV, Teplyashin IA, Timonin MA (2018) Development and study of a microwave reflex-radar level gauge of the nuclear reactor coolant. Izvestiya vuzov. Yadernaya Energetika [News of Higher Educational Institutions. Nuclear Power Engineering] 2: 185–190. [in Russian] https://doi.org/10.26583/npe.2018.2.02
- Needle D, Shepard SF (1998) Apparatus and methods for time domain reflectometry. Patent of the USA 5726578A Publ. 03/10/1998.
- Taranin VD (2015) Inductive level gauge for liquid metal coolant. Patent for Invention of the Russian Federation 2558010. No. 2013146131/28. Appl. 10/15/2013. Publ. 07/27/2015. [in Russian]
- Tarasov NA (2005) Using the method of impulse reflectometry to determine the damage of cable lines. http://reis.narod.ru/metod.htm [accessed Sep. 27, 2021] [in Russian]
- Trakhtenberg LI, Deniskin VP (1967) Device for non-contact measurement of the level and resistivity of molten metals. Patent for Invention of the USSR 197214. No. 1018402/26-10. Appl. 07/121965. Publ. 05/31/1967. [in Russian]
- Trenkal EI, Loshchilov AG (2016) Measurement of Liquid Levels by the Method of Pulse Reflectometry (Review). Doklady TUSUR [Papers of TUSUR] 19(4): 1–7. [in Russian] https://doi.org/10.21293/1818-0442-2016-19-4-67-73
- Vorontsov AC, Frolov PA (1985) Pulse measurements of coaxial communication cables. Radio i Svyaz Publisher, Moscow, 96 pp. [in Russian]