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LOW- AND MID-TEMPERATURE PRECISION BLACKBODY MODELS FOR RADIOMETRY AND RADIATION THERMOMETRY

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Low- and mid-temperature blackbody models with operating temperatures in the range 80–1200 K are considered. These types of models function as components of verification systems for preflight calibrations of onboard optical radiometric space equipment operating in the infrared range of wavelengths. Radiation sources with tunable temperature and models based on fixed reference temperature points of the melting–solidification phase transitions of Ga and In are described.
Keywords: *radiometry, photometry, optical thermometry, temperature scale, blackbody model.*

The series of blackbody models with radiation sources in the form of a cavity or plane-type radiation sources that have been developed at the All-Russia Research Institute of Optophysical Measurements (VNIIOFI) comprise models with variable operating temperatures and models with fixed temperatures at the phase transitions of pure substances [1–9]. Table 1 presents the basic characteristics of the optical sources, arranged as a function of the range of operating temperatures: from cryogenic (80–200 K) to low (200–400 K) and mid-level temperatures (400–1200 K).

Low-temperature blackbody models are intended for use in preflight calibration of onboard optical radiometric equipment that functions in the infrared band of wavelengths in cryo-vacuum chambers that simulate the conditions of orbital space flight. Such blackbody models have operated successfully as components of calibration systems at a number of space research institutes, for example, the Space Dynamics Laboratory (United States), German Aerospace Center, NEC-Toshiba Space Systems (Japan), Korean Research Institute of Standards and Science (South Korea), the Keldysh Research Center – the lead organization in Russia in the field of rocket engine construction and power engineering, and Russian Space Systems, an organization that specializes in the development, manufacture, and operation of space-based information systems.

Cu and Al-alloys are used as the construction materials of the radiating cavities of cryogenic and low-temperature blackbody models. The emissive capacity of a model, which is as close to 1 as possible, is achieved by covering the surface of the radiating cavities of the blackbody model with different types of black paints [10], in particular, Chemglaze Z-302 for the BB29gl model; Nextel Velvet 811-21 for the BB100, BB100-Vi, and BB-80/350 models; LORD AeroglazeZ306 for the VTBB model; and BB100-K1 and VLTBB for the VTBB model. Multizonal electrical heating of high-resistance spirals situated in different elements of the radiating cavities are employed in the VLTBB, VMTBB, and BB100-K1 models with the use of heat insulation from the cooling loop by means of liquid nitrogen or a liquid thermostat with circulation of the cooling agent.

Model VTBB – a vacuum blackbody model with tunable temperature developed expressly for operation as part of the Middle Background Calibration Facility (KRISS, South Korea) as a highly stable standard optical source with operating temperature in the range 213.15–363.15 K and aperture 30 mm. An airtight outer shell is provided in the model for operation at pressures $p \leq 1.3 \cdot 10^{-2}$ Pa, and the model is equipped with a flange for linking up with the vacuum chamber. The operating

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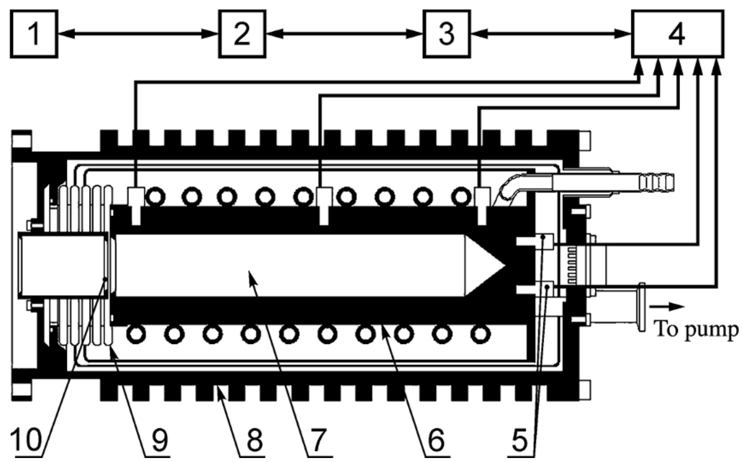

Fig. 1. VTBB blackbody model: *1*) thermostat; *2*) computer; *3*) multimeter; *4*) multiplexer; *5*) resistance thermometers; *6*) heat exchanger; *7*) radiating cavity; *8*) shell; *9*) bellows; *10*) aperture.

temperature in VTBB is stabilized by a Unistat 705 thermostat; a Keithley 2000 digital multimeter is used for measurement of the temperature of the radiation source; the VRL 100-3.5 guided-vane rotor vacuum pump maintains thermal insulation of the blackbody model from its outer shell and the environment, while the VD83M vacuum controller with power unit is necessary for measurement of the level of the vacuum near the heat exchanger (cf. Fig. 1).

Numerical modeling of the effective emissive capacity ε of the model was carried out on the basis of the Monte-Carlo algorithm with the use of the STEEP 3 computer program [11]. The normal effective emissive capacity of the cavity was calculated in the given temperature range at wavelengths in the range 5–30 μm under the assumption that the temperature irregularity along the length of the radiation source cavity is in the range 50–100 mK. If the temperature irregularity does not exceed 50 mK, at 213.15 K we obtain ε = 0.9997–0.9999, while with a temperature scatter less than 100 mK, the emissive capacity of the cavity ε at 363.15 K is at least 0.9998.

The shell of the VTBB model is manufactured from an Al alloy. The radiating cylindrical cavity with conical floor is in the form of a single solid block of copper with inner diameter of the cavity 40 mm, length 250 mm, and angle at the vertex of the cone 75°. The solid angle of radiation of the cavity of the blackbody model is bounded by an additional diaphragm. The heat exchanger, created in the form of a hollow copper cylinder, is mounted on the copper block of the radiating cavity. The heat exchanger tubes are provided with branch pipes at the end for connecting to the hoses of the liquid thermostat. Five platinum resistance thermometers are built into the wall of the copper block, with wires led outside through an airtight electrical plug and socket unit. The copper block is connected to the front and rear flanges of the shell by means of a flexible bellows made of stainless steel. The heat exchanger is insulated from the shell of the blackbody model by means of two cylindrical radiation shields made of stainless steel 0.5 mm thick. Degassing of the inner space of the radiation source shell produces thermal insulation of the copper block together with the heat exchanger and radiating cavity from the environment. The pump is connected by means of a flexible metal bellows to a vacuum branch pipe on the shell of the blackbody model.

A DW-Therm M90.200.02 heat exchanger is used for operation in the above temperature range in the VTBB and BB00-K1 models to produce circulation in the closed loop of the liquid thermostat. Under the conditions of a surrounding vacuum, the temperature gradient along the length of the radiating cavity of the VTBB model did not exceed ±40 mK.

BB100-V1 blackbody model. This model is a wide-aperture and low-temperature model intended for use as a standard radiation source for preflight calibration of space-based radiometers as well as radiation thermometers in the temperature range 240–350 K and infrared range of wavelengths 1.5–15 μm. The model was created in 2005 for the Keldysh Research Center and the NEC Toshiba Space Systems agency and JAXA (Japan) [4]. The basic characteristics of the model were obtained from the results of experiments performed in cryo-vacuum chambers in two regimes: 296 ± 3 K, p = 1.33 Pa and 77 K, p = 0.133 mPa.

In order to satisfy the requirements of long-term stability, the construction of the BB100-V1 model is based on unique precision models developed at the VNIIOFI in recent decades [2–4, 9, 12]. These blackbody models, provided with either tunable or fixed working temperatures, include BB100, BB300, BB900, BB1000, VTBB, BB29Ga, and BB156In, all of which operate in the temperature range 100–1000 K and are intended for calibration of space-based infrared radiometers and in precision radiometry at such metrological institutes as DLR and Physikalisch-Technische Bundesanstalt (PTB) in Germany, National Physical Laboratory in Great Britain, SDL in the United States, and the National Institute of Metrology and Xian Institute of Applied Optics(IAO) in China. The BB100-V1 model is provided with a cylindrical copper radiating cavity (coated on the inside with NEXTEL Velvet 821-11 black paint) , which is heated (cooled) by means of KRYO-51 (polydimethylphenylsiloxane) heat-transfer agent that circulates in the closed loop of the LAUDA liquid thermostat (Dr. R. Wobser GmBh & Co., Germany).

Technical characteristics of BB100-V1 blackbody model:

Range of working temperatures	240–350 K
Spectral range	1.5–15 μm
Effective emissive capacity of cavity	0.997 ± 0.001
Diameter of outlet aperture (nonprecision)	100 mm
Visual field of system	12 mrad (0.688°)
Temperature irregularity across field of outlet aperture	0.04 K
Temperature resolution of temperature controller	0.01 K
1 h Maximum temperature irregularity in thermal stabilization	±0.02 K
Warm-up time to working temperature	40–80 min
Power consumption	1600 W
Supply voltage	200 V

The liquid heat-transfer agent circulates throughout the length of the heat exchanger's copper pipe, which is wound around the radiation source cavity, a cylinder measuring 120 mm in diameter with volume 2260 cm^3. The inner coating of the cavity of the model in the given spectral range is characterized by an emissive capacity of at least 0.9 and is selected on the basis of results of an analysis of the optical properties of different black paints for the purpose of determining the degree of suppression of specular reflections and absorption of solar energy and for control of radiation losses. The effective emissivity of the cavity is determined from the results of computer modeling performed with the use of the STEEP 3 program. Reliable thermal protection is achieved by means of screen-vacuum insulation consisting of a multilayer polyethyleneteraphthalate film wrapped over the radiating cavity.

The heat exchanger is connected to an external thermostat (Proline PR1845 LCK 1891 from the firm of LAUDA). Computer software that functions in the LabView 5.0 programming environment was developed to control the uniformity of the temperature distribution in the cavity of the blackbody model. Four PRT-100 platinum precision resistance thermometers (MINCO, Inc., United States), mod. S278PD06, are built into the cavity, while a fifth resistance thermometer, mod. S1059PA5X6, is used in the feedback loop of the thermal stabilization system. Calibration traceability of the platinum resistance thermometers is assumed for only one of the thermometers. The signals from the PRT-100 thermoresistors for use in measurements enter the input of the 20-channel scanner of an HP-34970A multimeter (Agilent Technologies, United States).

The outer case of the model is manufactured from stainless steel with diameter 214 mm. The radiating cavity, which has an inner diameter of 120 mm and length 200 mm, consists of three basic parts, a cylindrical central (radiating) section and rear and front flanges. The model, together with the nozzles of the copper heat exchanger, is 500 mm in length. The length of the connecting hoses and cables measures 5 m from the inner and outer surfaces of the vacuum chamber.

The BB100-V1 model is mounted either vertically or horizontally in the working position in the cryo-vacuum chamber and may be connected to the inlet flange of the customer's device which is to be calibrated. The reference PRT-100 contains a special dismountable holder by means of which it may be periodically calibrated. It is situated at the center of the surface of the floor outside the radiating cavity with a V-shaped profile of small concentric grooves. In order to satisfy the customer's requirements for the length of the connecting polymer (Viton rubber) hoses, there must at least 20 m space between the blackbody model situated inside the vacuum chamber and the thermostat outside it, the latter being equipped with two pumps, a suction pump and an exhaust pump.

BB100-K1 blackbody model. The model was created for operation as part of a calibration unit developed at KRISS (South Korea) on the basis of a Russian standard infrared radiation source. The BB100-V1 blackbody model was used as the prototype. The BB100-K1 model is provided with an outlet aperture 100 mm in diameter and is intended for use in calibration of laboratory-scale radiometric equipment, radiometers, and radiation thermometers as a standard source of infrared radiation for calibration in the temperature range 233–363 K corresponding to the wavelength range 1.5–15 μm. The model may be used under cryo-vacuum conditions, when the radiation source is situated entirely inside the chamber; inside a chamber filled with nitrogen or an inert gas or in a dry air atmosphere, when the radiation source is completely situated within the work space of the chamber; or in open air at ambient temperatures in the range 253–363 K with mandatory observance of conditions that prevent the formation of hoarfrost in the radiating cavity below the dew point.

The temperature distribution along the length of the cylindrical radiating cavity and across its floor is recorded by five precision platinum thermoresistors (PRT-100) and a digital multimeter equipped with a multichannel card scanner. Two thermoresistors are located along the cavity of the blackbody model while another three are built into its floor with the middle one removable for purposes of recalibration. Like the VTBB model, a UNITSTAT 705 liquid thermostat is used for thermostabilization of the BB100-K1 with error ±0.01°C.

The BB100-K1 functions stably both within the vacuum chamber in the working range 213–363 K as well as in dry air or in an inert gas in the range 233–363 K with the use of an additional nozzle at the outlet aperture. The effective emissive capacity of the cavity of the BB100-K1 model with inner coating of LORD Aeroglaze Z306 black paint is 0.996 ± 0.001.

Experimental investigations, including measurements of the temperature uniformity and thermography of the VTBB and BB100-K1 models, were performed at KRISS (South Korea) in September, 2009. The temperature gradient at the aperture for both blackbody models did not exceed ±50 mK in a dry air atmosphere in the range of operating temperatures 233–363 K.

VLTBB blackbody model. The model was created as a highly stable standard radiation source in the temperature range 100–450 K that functions in a vacuum chamber with shields, cooled by liquid nitrogen at a pressure not greater than 10^{-3} Pa in the calibrating system of the PTB metrological institute (Germany). The model is supplied with a deep radiating cavity, in the form of a cylinder 40 mm in diameter and 250.6 mm in length, produced from oxygen-free copper the inner surface of which is covered with LORD Aeroglaze Z306 black paint with cooled exit aperture 20 mm in diameter. Three-zonal regulation of the temperature of the model is achieved by means of course and precision controllers. Coarse thermal regulation is realized by cooling with liquid nitrogen and heating by means of electric heaters. In precision thermal regulation, the temperature instability and temperature gradient along the length of the cavity is in the range 20 mK over the entire range of working temperatures of the blackbody model. The effective emissive capacity at 150 K in the spectral range 10–25 μm amounts to 0.9996.

VMTBB blackbody model with variable operating temperatures. This model was created for operation as a component of a system at PTB in an operating temperature in the range 420–700 K. The system is intended for calibration of radiation thermometers under the conditions of a vacuum. The radiating cavity, which is produced from oxygen-free copper, is 426 mm in diameter and 240 mm in length with effective emissive capacity in the case of preliminary nickel plating of the cavity prior to application of the black coating amounting to 0.9994. Three-zonal regulation with the use of temperature controllers based on a proportional-integro-differential algorithm was used to achieve the optimal temperature uniformity along the length of the cavity. The temperature was tracked by means of 15 PRT-100 precision thermoresistors. Studies carried out at PTB demonstrated that the instability of the radiation temperature of the blackbody model is in the range ±20 mK while the temperature irregularity along the length of the cavity of the model over the entire range of operating temperatures does not exceed ±100 mK. The results of measurements and a detailed description of the construction of the last two models are presented in [4, 5].

Conclusion. Precision low- and mid-temperature blackbody model radiation sources have been developed over the past 30 years at the VNIIOFI. Cavity radiation sources with tunable temperature have found use as components of standard systems both in Russia and at the national metrological centers of leading countries around the world. These blackbody models are used in the range 100–700 K in low-phonon cryogenic-vacuum chambers of systems employed in preflight calibration of onboard radiometric equipment, with their temperature irregularity over the entire range of working temperatures not exceeding ±50 mK.

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