Progress Report on Radiation Dosimetry at the VNIIM

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This report gives an overview of radiation dosimetry activities at D. I. Mendeleyev Institute for Metrology (VNIIM) from June 2017 to May 2019 for the meeting of Section I (x- and gamma rays, charged particles) of Consultative Committee for Ionizing Radiation (CCRI), 5–6 June 2019.

In the VNIIM laboratory for x-ray, gamma, bremsstrahlung and beta radiation dosimetry there are 9 members (6 scientists, 2 engineers and 1 technician).

National primary standards development

The primary standard for x-rays and gamma radiation air kerma

The VNIIM air kerma primary standard provides reproduction, storage and transfer of x-rays and gamma radiation air kerma unit and maintain measurements, calibrations and verifications of dosimetry instruments in medicine, ecology, radiation safety, space research, defectoscopy, etc.

The primary standard for gamma radiation air kerma includes the set of four graphite-walled cylindrical cavity ionization chambers; the primary standard for low-energy and medium-energy x-rays air kerma includes the set of four free-air ionization chambers. More than 70 qualities, including therapeutic, diagnostic, radiation protection, CCRI and mammography (with W and Mo), are established.

Following the recommendations of ICRU Report 90 “Key data for ionizing-radiation dosimetry: measurement standards and applications” and the subsequent decision of the CCRI(I), re-evaluation of the VNIIM standard for x-rays and gamma radiation air kerma has been done in 2018.

The changes include:

- Regarding the measurements with the free-air chambers:

  - Increase in the standard uncertainty for the value of the average energy to create an ion pair in air, W_{air} from 0.15 % to 0.35 %.

  - Application of an energy-dependent W_{air} value for electron energies below 10 keV which is realized through implementation of combined correction factor $k_{ii}k_{w}$. To receive the product $k_{ii}k_{w}$ for the VNIIM radiation qualities the $k_{ii}k_{w}$ monoenergetic values presented in the Report were applied to the particular quality spectrum. The uncertainties used arise from D. Burns recommendations.

- Regarding the measurements with the graphite-walled cavity chambers:

  - Implementation of the revised value 33.72 eV for the product of the average energy to create an ion pair in air, W_{air} and the electron stopping-power graphite to air ratio, $s_{g,air}$ for Co-60 with the relative standard uncertainty 0.08 %.

  - Adoption of the value 34.05 eV for the product $W_{air}{\cdot}s_{g,air}$ for Cs-137 ($s_{g,air}$ = 1.0023) with the standard uncertainty of 0.12 % according to D. Burns deduction. It includes the recommendation of the Report to increase the mean excitation energy of graphite, I_g from 78 eV to 81 eV, with a corresponding decrease in the standard uncertainty from 4 eV to 1.8 eV, and the use of the crystalline density in the stopping-power evaluation, and takes an advantage of lower uncertainty for $W_{air}{\cdot}s_{g,air}$ for Co-60 also.

The changes in the uncertainties of the primary standard for x-rays and gamma radiation air kerma are presented in Table 1 and will be implemented from July 2019.

Table 1. The main characteristics of the VNIIM primary standard
for x-rays and gamma radiation air kerma and their changes according to ICRU Report 90

Radiation quality	Standard	Quantity	Range	Change to the standard	Existing uncertainty $u_{0C} \cdot 10^2$	Revised uncertainty $u_{0C} \cdot 10^2$
Gamma radiation	Cavity ionization chambers ND1005, C30, IKG40/2-2, IKG80/4	Air kerma	$1 \cdot 10^{-7}$–$5 \cdot 10^{-2}$ Gy	from –0.81 % to –0.83 %	0.19–0.38	0.18–0.38
		Air kerma rate	$1 \cdot 10^{-8}$–$5 \cdot 10^{-3}$ Gy/s			
Low-energy x-rays 5–50 kV	Free-air chambers IK 5-20, IK 20-60 and IK 10-100	Air kerma	$4 \cdot 10^{-5}$–20 Gy	from –0.47 % to –0.19 %	0.24–0.34	0.41–0.47
		Air kerma rate	$4 \cdot 10^{-6}$–2 Gy/s			
Medium-energy x-rays 50-320 kV	Free-air chambers IK 10-100 and IK 70-300	Air kerma	$3 \cdot 10^{-5}$–1 Gy	from –0.19 % to –0.06 %	0.21–0.31	0.39–0.45
		Air kerma rate	$3 \cdot 10^{-6}$–$1 \cdot 10^{-2}$ Gy/s			

The primary standard for beta radiation absorbed dose to tissue

The primary standard for beta radiation absorbed dose to tissue was established in 1962; in 1982 a new extrapolation chamber was built and since that time there were no significant changes in the standard. Expansion of beta radiation applications and development of beta radiation dosimetry over time have led to emergence of new requirements for the reference equipment for beta radiation measurements. Therefore, during the last 3 years the primary standard was completely renovated.

The following improvements to the beta primary standard were made:

– new measurement facility UEDAB-1 for beta radiation absorbed dose to tissue reproduction and transfer;

– new automatically controlled primary standard extrapolation chamber MEK-1;

– new automatically controlled irradiation workbench for calibration of beta dosimeters, dose-rate meters and beta radiation sources in terms of absorbed dose to tissue at depth of 0.07 mm in tissue-equivalent slab geometry and individual dosimeters of beta radiation in terms of dose-equivalent quantities against the primary standard;

– new measuring system, including modern equipment with high precision electrometer, barometer, thermometer and humidity probe.

– transfer standard TEB-1 based on the plane-parallel ionization chamber for calibration of beta radiation sources and dosimetry facilities against the primary standard;

– new software that allows to control UEDAB-1 facility as well as data acquisition and analysis of measuring information in automatic mode.

The characteristics of MEK-1 extrapolation chamber are presented in Table 2. The view of the chamber is demonstrated in Figure 1.

The chamber is suitable for measurements with medical and industrial beta sources such as Ru-106/Rh-106, Sr-90/Y-90, Kr-85 and Pm-147 at distances over 100 mm from the surface of the source in the ranges of absorbed dose to tissue from $3 \cdot 10^{-4}$ to $1 \cdot 10^{-1}$ Gy and absorbed dose rate to tissue from $5 \cdot 10^{-6}$ to $1 \cdot 10^{-3}$ Gy/s.

The chamber has a very thin entrance window made of aluminized polyethylene terephthalate film. Replaceable tissue equivalent filters can be added to the entrance window in order to change its thickness from 5 mg/cm^2 to 300 mg/cm^2 of tissue. The chamber air gap is adjustable automatically from 0.25 to 2.5 mm with accuracy of 1 μm.

Table 2. The main characteristics of the VNIIM primary standard extrapolation chamber MEK-1 for beta radiation absorbed dose to tissue measurements

Characteristic	Value
Entrance window (potential electrode): – material – diameter – thickness (surface density)	 aluminized polyethylene terephthalate 100 mm less than 1 mg/cm^2
Moving electrode unit: – material – thickness	 PMMA 31 mm
Collecting electrode: – material – diameter – the guard ring width – the insulation gap width – the insulation gap depth	 graphite-coated PMMA (30±0.3) mm 15 mm 0.2 mm 0.2 mm
Range of working distances between the moving electrode unit and the inner surface of the entrance window	from 0.25 to 2.50 mm with the step of 0.001 mm
Entrance window thickness (replaceable filters)	5 mg/cm^2, 7 mg/cm^2, 10 mg/cm^2, 40 mg/cm^2, 60 mg/cm^2, 100 mg/cm^2, 300 mg/cm^2
Dimensions of the chamber – length – height – width	 310 mm 290 mm 170 mm
Mass of the chamber	6.7 kg
Field strength	±10 V/mm
Leakage current	less than $5\cdot10^{-15}$ A

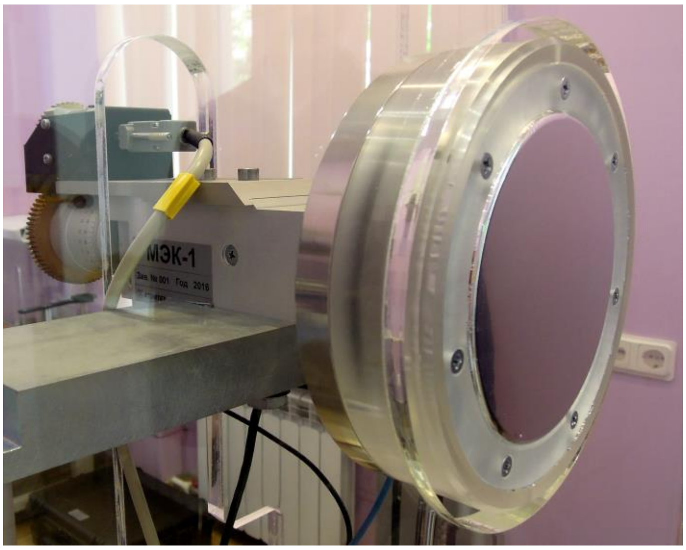


Fig. 1. The primary standard extrapolation chamber MEK-1 for beta radiation absorbed dose to tissue measurements

General view of UEDAB-1 facility with MEK-1 extrapolation chamber and the radiation workbench is presented in Figure 2. During the measurements of absorbed dose to tissue beta source is mounted in the special holder installed on the irradiation unit at the reference distance from the chamber. UEDAB-1 facility also allows to perform testing and calibration of individual dosimeters. The video monitoring system is used for remote reading of dosimeters. The laser centering system provides adjustment of dosimeters along the beam axis. Due to high level of automation of measurement processes using UEDAB-1 facility, radiation safety of the upgraded primary standard was enhanced.

Fig. 2. UEDAB-1 facility for beta radiation absorbed dose to tissue measurements

The primary standard also includes UEDB-2 facility with EK-2M extrapolation chamber which was the part of the primary standard before the upgrade. EK-2M extrapolation chamber allows to measure the absorbed dose to tissue in the range from $1 \cdot 10^{-1}$ to $1 \cdot 10^{2}$ Gy and beta radiation absorbed dose to tissue in the range from $1 \cdot 10^{-3}$ to 1 Gy/s. The correction factors for EK-2M chamber were re-determined according ISO 6980.

Metrological characteristics of the renovated primary standard are presented in Table 3.

The VNIIM participation in the EURAMET supplementary comparison of personal dose equivalent at 0.07 mm and 3 mm depth, $H_p(0.07)$ and $H_p(3)$, for beta radiation with the renovated primary standard is postponed to 2020.

Table 3. The metrological characteristics of the VNIIM primary standard beta radiation absorbed dose to tissue

Characteristic	Quantity	
	Absorbed dose to tissue	Absorbed dose rate to tissue
Range	$3\cdot10^{-4}$–$1\cdot10^{2}$ Gy	$5\cdot10^{-6}$–1 Gy/s
Type A standard uncertainty u_{0A}	$1\cdot10^{-2}$	
Type B standard uncertainty u_{0B}	$8.3\cdot10^{-3}$–$1.2\cdot10^{-2}$	
Expanded standard uncertainty U_0 (k = 2)	$2.6\cdot10^{-2}$–$3.2\cdot10^{-2}$	

The primary standard for flux, flux density and fluence of electrons, energy flux, energy flux density and energy fluence of electrons and bremsstrahlung radiation for energy up to 50 MeV

Metrology characteristics of the standard are presented in Table 4.

Table 4. The main characteristics of the VNIIM primary standard for flux, flux density and fluence of electrons, energy flux, energy flux density and energy fluence of electrons and bremsstrahlung radiation for energy up to 50 MeV

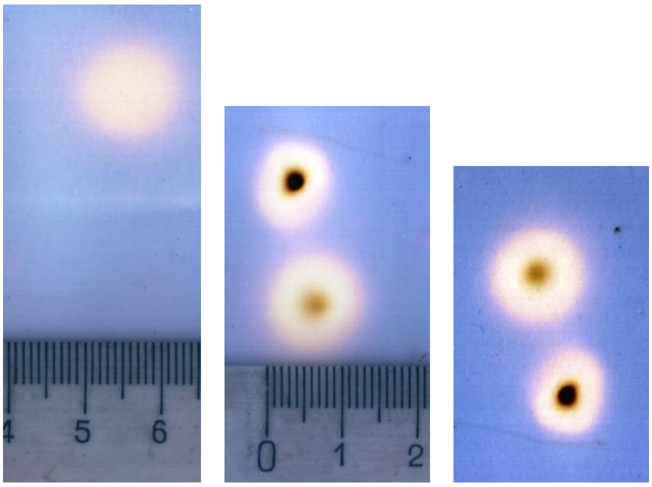
Radiation quality	Standard	Quantity	Range	$u_{0C}\cdot10^{2}$
Electrons with energy 0.1–50 MeV	Faraday cylinder CF-3, CF-4	Flux of electrons	10^{10}–10^{21} s^{-1}	0.71
	Faraday cylinder CF-REB; Diamond detector UDMC-1k	Flux density of electrons	10^{8}–10^{19} $cm^{-2}\cdot s^{-1}$	1.2
	Faraday cylinder CF-REB, CF-3	Fluence of electrons	10^{9}–10^{21} cm^{-2}	1.2
	Calorimetric detector KFE-1, KCF-1	Energy flux of electrons	10^{-4}–10^{3} W	0.71
	Calorimetric detector KS-1S, KCF-REB	Energy flux density of electrons	10^{-5}–10^{2} $W\cdot cm^{-2}$	1.2
	Faraday cylinder and calorimeter KCF-REB	Energy fluence of electrons	10^{-3}–10^{3} $J\cdot cm^{-2}$	1.2
Bremsstrahlung radiation with energy 0.1–50 MeV	Calorimetric detector KFE-F; Thick-walled ionization chamber IKV-6	Energy flux density of bremsstrahlung radiation	10^{-5}–10^{2} $W\cdot cm^{-2}$	1.2
	Thick-walled ionization chamber IKV-6	Energy flux of bremsstrahlung radiation	10^{-4}–10^{3} W	0.71
	Thick-walled ionization chamber IKV-6	Energy fluence of bremsstrahlung radiation	10^{-3}–10^{3} $J\cdot cm^{-2}$	1.2

Since 2016 the VNIIM maintains an industrial linear accelerator UEL 5/20. Within the commissioning of the accelerator the study of the spatial-geometry characteristics of the fields of electron radiation at the output of the rotary magnet was started in 2018. The ranges of the energy of electron radiation and the electron flux (beam current) at 20 mm distance of the exit window of the accelerator were determined. The results are presented in Table 5.

Table 5. Parameters of the field of electron radiation at the output of UEL 5/20 accelerator in vertical direction

Electron beam current, A	Electron flux, s^{-1}	Mean energy of the electron beam, MeV
$1.20 \cdot 10^{-6}$	$7.491 \cdot 10^{12}$	12
$2.21 \cdot 10^{-6}$	$1.380 \cdot 10^{13}$	3
$2.40 \cdot 10^{-6}$	$1.498 \cdot 10^{13}$	3
$2.60 \cdot 10^{-6}$	$1.623 \cdot 10^{13}$	3
$3.20 \cdot 10^{-6}$	$1.998 \cdot 10^{13}$	12
$7.80 \cdot 10^{-6}$	$4.869 \cdot 10^{13}$	10

The results of evaluation of the spatial-geometry characteristics of the electron beam at 20 mm distance from the exit window of accelerator in vertical direction using CVID color indicators are presented in Figure 3.



3 МэВ 10 МэВ 12 МэВ

Fig. 3. Geometric parameters of the electron beam (cross-section diameter) in vertical direction

Recently the investigation of the conversion coupling coefficients between radiometry and dosimetry parameters of beta radiation sources was started. To produce the conversion coupling coefficients as a ratio of absorbed dose rate in the phantom and electron flux density affecting the phantom the measurements were performed with $^{90}Sr+^{90}Y$ BIS-10 and BIS-50 sources. To determine the electron flux density distribution along the beam primary standard diamond detector and Faraday cylinders were used. The measurements of absorbed dose rate of beta radiation were performed using the ionization chamber calibrated against the primary standard of beta radiation absorbed dose to tissue. The expanded standard uncertainty of these measurements was less than 2.5 %. The conversion coupling coefficients were received at different distances from the source.

The primary special standard for pulsed x-rays exposure (air kerma), exposure rate (air kerma rate), energy flux and energy flux density

The standard provides reproduction and storage of pulsed x-rays exposure (air kerma), exposure rate (air kerma rate), energy flux and energy flux density units. The standard was established in 1982. Since that time no significant changes were made.

In 2017–2019 slight upgrade of the measurement system was performed. New measurement system includes modern equipment such as high precision electrometer, thermometer, barometer and humidity probe.

Metrology characteristics of the standard are presented in Table 6.

Table 6. The main characteristics of the VNIIM primary special standard for pulsed x-rays exposure (air kerma), exposure rate (air kerma rate), energy flux and energy flux density

Radiation quality	Standard	Quantity	Range	$u_{0C}\cdot 10^2$
Pulsed x-rays	Free-air chamber IK-01	Exposure	$8\cdot10^{-7}$–$3\cdot10^{-4}$ C·kg^{-1}	1.6
	Free-air chamber IK-01	Exposure rate	$8\cdot10^{-9}$–$3\cdot10^{-5}$ A·kg^{-1}	1.6
	Calorimeter KL-01	Energy flux of pulsed x-rays	$5\cdot10^{-6}$–$3\cdot10^{-5}$ W	2.6
	Calorimeter KL-01	Energy flux density of pulsed x-rays	10^{-2}–10^{-1} W·m^2	2.6

International activities

In September 2018 the VNIIM hosted the 15th Meeting of the COOMET Technical Committee 1.9 “Ionizing radiation and radioactivity”. Within the frame of the meeting the applied research conference devoted to the 100th anniversary of the Ionizing Radiation Department was held.

The VNIIM took part in the COOMET.RI(I)-S3 comparison of the national primary standards of air-kerma for x-radiation qualities used for radiation protection and diagnostic radiology in July 2017.

In February and March 2019 the training sponsored by the IAEA was organized for the colleagues from AF JSC “National expertise and certification center”, Kazakhstan.

Measuring instruments calibration and verification

In 2017–2019 the VNIIM performed calibrations, verifications and comparisons for accredited dosimetry calibration laboratories, atomic power stations, clinics and manufacturers of dosimetry instruments and sources.

Calibrations and verifications of diagnostic dosimeters are performed in terms of air kerma, air kerma to length product, air kerma to area product. Therapeutic level calibrations and verifications are carried out in terms of x-rays and gamma radiation air kerma and absorbed dose to tissue of beta radiation. Industrial level calibrations and verifications are performed in terms of gamma radiation air kerma, flux, flux density, fluence, energy flux, energy flux density and energy fluence of photons and charged particles. Protection level and personal dosimetry instruments calibrations and verifications are carried out in terms of x-rays and gamma radiation air kerma, beta radiation absorbed dose to tissue and dose-equivalent quantities. Reference radiation qualities are those internationally recommended.

Ir-192, Co-60 and I-125 sources for brachytherapy and well-type ionization chambers used in clinics and in industry were calibrated in terms of air kerma strength.

Helio-geophysical measuring equipment was calibrated in terms of flux density rate of electrons and protons.

More than 190 calibrations and verifications of working standards, including dosimetry x-rays, gamma and beta radiation sources were done. More than 2200 calibrations and verifications of measuring instruments for x-rays, gamma and beta radiation were performed: about 110 calibrations and verifications of diagnostic dosimetry instruments; about 50 calibrations and verifications of therapeutic level measuring instruments; about 35 – of industrial level; the rest were calibrations and verifications of protection level measuring instruments and personal dosimeters.

Secondary standards calibrations were done for Belorussian State Institute of Metrology (BelGIM) (Minsk, the Republic of Belarus), SNIIP (Moscow), “TEST-St. Petersburg” (St. Petersburg), VNIIEF (Sarov), Ural CSM (Sredneuralsk) and for the VNIIM itself.

Measuring instruments testing for type approval

The VNIIM is a state testing center of Russia and is responsible for type approval checkout of imported and home-produced dosimetry devices.

For the last two years 10 Russian and foreign measuring instruments were tested for type approval: air kerma to area product measuring instruments KermaX plus 120-131, KermaX plus 120-130 CAN, KermaX plus DDP, KermaX plus 120-132 and KermaX plus 120-160 LFD (by IBA Dosimetry, Germany); multifunctional dosimeters NOMEX Multimeter (by PTW-Freiburg, Germany); dosimeters-radiometers RadiaScan-801 (by “Angioskan-Electroniks”, Moscow, Russia); dosimeters RaySafe X2 (by Unfors RaySafe AB, Sweden); dose-rate meters IMD-B (by TSNII RTK, St. Petersburg, Russia); dosimeters DKS 3000 (by “Radiko”, Obninsk, Russia).

Regulations development

In 2017–2019 calibration and measurement procedures with the air kerma primary standard for x-rays and gamma radiation were revised; procedures of measurement, calibration and verification were developed for different types of dosimetry devices, including air kerma to area product and air kerma to length product measuring instruments, as well as multifunctional dosimeters that may be used for x-ray tube voltage and HVL measurements.

Publications and talks

[1] Trofimchuk S. G., Oborin A. V., Fedina S. A., Tsvetkov I. I., Villevalde A. Y. Progress Report on Radiation Dosimetry at the VNIIM, CCRI(I)/17-18, CCRI Section I 23nd meeting working documents: x- and gamma rays, charged particles, 2017

[2] Лукашевич Р. В., Гузов В. Д., Кожемякин В. А., Оборин А. В. Сцинтилляционные блоки-компараторы для измерений мощности кермы в воздухе в диапазоне от 0.03 нГр/с до 50 нГр/с, Метрология и приборостроение, № 1 (75), Минск, 2017, с. 33–37 / Lukashevich R. V., Guzov V. D., Kozhemyakin V. A., Oborin A. V. Scintillation units-comparators for air kerma rate measurements in the range from 0.03 nGy/s to 50 nGy/s, Metrology and instrumentation, № 1 (75), Minsk, 2017, P. 33–37

[3] Трофимчук С. Г., Оборин А. В., Моисеев Н. Н., Алексеев И. В. Комплекс государственных первичных эталонов ВНИИМ им. Д. И. Менделеева в области измерений ионизирующих излучений, Сборник аннотаций докладов Международной научно-практической конференции “175 лет ВНИИМ им. Д. И. Менделеева и Национальной системе обеспечения единства измерений”, Санкт-Петербург, 2017, с. 170–171 / Trofimchuk S. G., Oborin A. V., Moiseev N. N., Alekseev I. V. The VNIIM primary standards for ionizing radiation measurements, The collection of reports summary of the International scientific and applied research conference “175th anniversary of the VNIIM and National measurement integrity system”, St. Petersburg, 2017, P. 170–171

[4] 100 лет отделу измерений ионизирующих излучений ВНИИМ им. Д. И. Менделеева: история и современность, Сборник статей и мемуаров под ред. С. Г. Трофимчука, Санкт-Петербург, Нестор-История, 2018, 304 с. / 100th anniversary of the VNIIM ionizing radiation department: history and modernity, The collection of papers and essays edited by S. G. Trofimchuk, St. Petersburg, 2018, 304 p.

[5] Пронин А. Н., Трофимчук С. Г., Оборин А. В. Опыт ВНИИМ им. Д. И. Менделеева по совершенствованию системы метрологического обеспечения в ядерной медицине, Медицина: целевые проекты, № 33, 2019, с. 20–22 / Pronin A. N., Trofimchuk S. G., Oborin A. V. The VNIIM experience in development of metrological support system for nuclear medicine, Medicine: target projects, № 33, 2019, P. 20–22

[6] Оборин А. В., Гришин Д. С. Повышение точности дозиметрических измерений в брахитерапии, Видеонаука: сетевой журнал, №1(13), 2019 / Oborin A. V., Grishin D. S. The increase of dosimetry measurements accuracy in brachytherapy, Videoscience: on-line journal, №1(13), 2019 https://videonauka.ru/stati/22-izmeritelnaya-apparatura-i-oborudovanie/220-povyshenie-tochnosti-dozimetricheskikh-izmerenij-v-brakhiterapii

[7] Villevalde A. Y. Dosimetry laboratory: primary standards, present day state and plans, ICRM WG Meeting, Saint-Petersburg, 2018 (oral report)

[8] Виллевальде А. Ю. Ключевые вопросы CCRI(I)-2017, 15 заседание Технического комитета 1.9 КООМЕТ, Санкт-Петербург, 2018 (устный доклад) / Villevalde A. Y. Key questions of the CCRI(I)-2017, The 15th Meeting of the COOMET Technical Committee 1.9, Saint-Petersburg, 2018 (oral report)