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THE PROS AND CONS OF MODERN LIGHT-EMITTING DIODE AND TRADITIONAL TECHNOLOGIES FOR STREET ILLUMINATION

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ABSTRACT

Features of perception of visual images under conditions of limited illuminance typical for roads and motorways, as well as safety issues for traffic and pedestrians are considered.

It is recommended that specific applications of illumination devices are carefully analysed and that various types of light sources with different spectra are used to provide safe and optimal solutions for problems of illumination of roads and pedestrian crossings.

As a result of the analysis performed, a conclusion reached that using illumination devices with light emitting diodes for illumination of pedestrian crossings is most appropriate. For roads and motorways, retention and further development of state-of-the-art illumination systems based on effective high pressure sodium lamps (HPSL) of ever evolving generations.

Keywords: light sources, HPSL, light-emitting diodes, light-emitting diode modules, electron ballast, luminaires with light-emitting diodes, *Osram*, *2 Y*, *3 Y*, *4 Y*, *6 Y*, *Galad*

ATTENTION TO DETAILS

With the appearance of new light sources (LS), including light-emitting diodes, with the rapid development of the lighting industry and hundreds of new manufacturers emerging on the market, the question of applicability of a specific illumination solution has become very topical.

Intuitively, it is clear that illumination of classrooms or production workshops must perform to specific illumination standards and additional requirements specific to features like biorhythms of a person performing an activity or the stroboscopic effect from moving machine parts, which has implications for work safety. Therefore, it is very dangerous and irresponsible to extend and distribute technologies, however modern and fashionable they were, to all applications and all types of illumination. In the following article we explore specific features of roadway and pedestrian crossings illumination. From the first glance, in can easily seem that these objects are very similar, because they are in direct contact with each other, and so the same LDs can be deployed on them. The following sections consider whether this is the case.

A STRATEGY FOR THOUGHT-OUT ENERGY SAVING

Almost all developed countries have embarked on energy saving programmes involving different sectors, including illumination field as well. This involves introducing new technologies, but also perfecting long proven technologies and solutions, which continue to develop, for example, electron ballasts and illumination control systems [1, 2].

It is not by chance that in many countries, in addition to international and local standards, programmes and strategies for street illumination are also being developed. For example, Durham City Council, the administrative centre of County Durham in Great Britain, has developed its own programme “Policy of street illumination for Durham city”. A similar programme is being implemented in the county of Hampshire. These initiatives are something from which Russian lighting planners can learn, or at least consider the degree to which our experience and existing requirements to LDs are thought over and whether they reflect an integrated approach to street illumination.

For example, the programmes which exist in Great Britain [3, 4] solve the following problems:

- Effective use of roads for vehicles, cyclists and pedestrians;
- Presence of schools, trade and entertainment centers, sports centers, churches, public buildings, medical institutions in immediate proximity of a traffic way (all of this considerably influences the likelihood of night-time road use);
- Location of roads within the city infrastructure and the type of these roads, for example, city road, country road, etc.;
- Environmental impacts, including undesirable background light on adjoining territories, residential buildings and light pollution of the atmosphere.

Within these documents, objects with artificial illumination clearly divided into specified categories. For example: an *E1* area classification denotes national parks, areas of unique natural beauty, and sites of special scientific interest; an *E2* area classification means an area of lowered illumination levels, areas of countryside, which do not fit under E1 criteria; *E3* area classification refers to an area of medium levels of illumination (a city landscape), an area of raised illumination level (main roads, areas with high criminal activity, city centers; pedestrian crossings, subways and traffic lights). The documents also clearly specify the illumination standards used, the types of LSs, luminaires, illumination and arm supports, as well as any requirements for corrosion protection. Requirements for the height of masts and illumination supports, for illumination control systems, electric power consumption and servicing frequency are set out separately. For example, in Italy, a minimum distance between illumination supports is regulated: it should be at least 3.7 support heights or more. This approach not only influences LD lighting parameters but also makes good economic sense: not to install supports like a palisade or fence, which would significantly increase the initial LD costs. The distance between many street LD supports, standard for Russia, is 33 m at a height of 9 m; the ratio of 3.67 is close to that used in Italy. Many street luminaires with light emitting diodes installed at a height of 8 m, can have a distance between supports of 25 m, which leads to high frequency support installation, at a ratio of 3.1, in other words, a higher LD cost. This is often the consequence of unsatisfactory light distribution from luminaires with light emitting diodes, which in most cases shine "underneath themselves". This is an important scenario to consider because the large majority of external illumination LDs are installed and operated with public funding.

Different illumination solutions are required for different objects of illumination, and it is necessary to consider the specific details and features of each case. Specific requirements must extend to illumination equipment, metal structures, and the LSs used. At this time, there are no universal solutions, which would suit all or even most applications. The same is the case with HPSLs, and with light-emitting diode LSs. Professional light engineers usually say: "There should be light, only where it is needed, and only the kind of light that is needed".

OSRAM Company is a world leading manufacturer of illumination equipment and LSs, including light-emitting diode LSs, as well as an expert on illumination. When it comes to street illumination, OSRAM considers the safety of pedestrians and drivers, the impact on adjoining territories and environment as its priorities.

SOME FACTS

The necessity of high quality illumination for roads and motorways and pedestrian crossings seems to be obvious. However, it is not absolutely clear, what are really high quality illumination and why this question should be considered so carefully, with numerous details, which are not always obvious. To understand this question, we need to begin from the following facts:

- According to the National Highway Traffic Safety Administration (*NHTSA*) of the USA [5], 30 % of accidents on roads with pedestrians occur within the time interval from 20:00 till 24:00.
- The number of fatal accidents in 2010 increased by 4 % in comparison with 2009 (*NHTSA* data).
- The number of fatal accidents involving pedestrians amounted to about 12 % of the total number of such cases of the all road accidents (*NHTSA* data).
- In densely populated areas significant levels of motor transport and a high traffic intensity, pedestrian death rate can reach 27 % of the total number of such cases in all road accidents (*NHTSA* data).

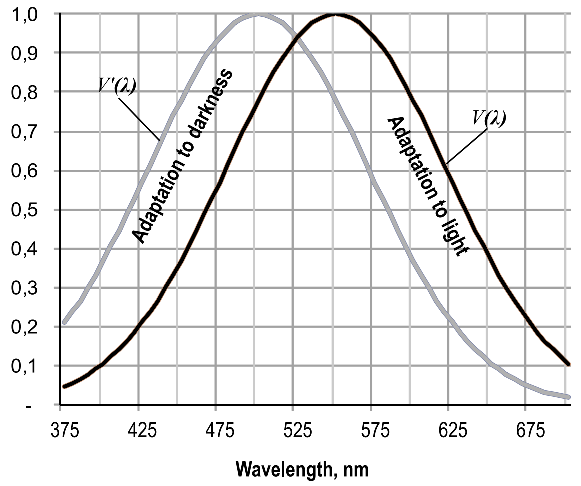

Fig. 1

• A review of the *EuroTest* European organisation (2009) [6] shows that annually in all European countries, over eight thousand pedestrians perish in road accidents. Almost one in four road accidents occurs at a pedestrian crossings.

• An analysis of 310 pedestrian crossings in 31 European cities showed that even pedestrian crossings with traffic lights can be unsafe, and their structure needs improvement. The best pedestrian crossings appeared to be in Bratislava, Rotterdam and Strasbourg. 60 % of the all tested crossings were estimated as "very good" or "good", and 53 crossings of 310 were judged to be of a poor standard.

One of the *EuroTest* recommendations regarding the structure pedestrian crossings and their illumination, was the use of a "blinking green" light as a transitional stage between stable green and red light, which would allow people to make sound decisions about crossing based on their own physical state. This, together with the devices of return time readout and new technological solutions, including traffic lights with light emitting diodes, will provide better visibility, especially at night time, and prevent many accidents. These measures are especially important for improving living conditions for disabled pedestrians and the increasingly ageing general population.

THE PHYSIOLOGY OF NIGHT VISION

This section will consider features of human sight at night. It makes sense to consider the effectiveness of road and pedestrian crossings illumination within the context of the mechanisms of night vision. There are two photosensitive structures in eye retina responsible for sight: rods and cones. Cones are concentrated in the retina centre and provide clear central sight, recognition of colour and small details under conditions of daytime (photopic) sight [7]. Rods are located outside of retina centre and provide peripheral sight, allowing eyes to perceive movement. The eye's ability to see under conditions of very low illumination (twilight, or scotopic sight) may be due to rods. The known curves of relative spectral luminous efficacy for day sight *V (λ)* and night sight *V' (λ)* are given in Fig. 1.

Under twilight conditions, at a medium level of illumination, between day and night, twilight (mesopic) sight occurs. Both rods, and cones are involved, but rods with their greater photosensitivity, play a dominant role in the twilight sight, and their ability to differentiate colours decreases.

Cones are most sensitive at a wave length of $\lambda_{max} \approx 555$ nm (within the yellow-green spectrum interval), and rods – at $\lambda_{max} \approx 515$ nm (green-blue interval). The activation of different parts of retina under different conditions of illumination means that in bright sunlight, when cones are more active, red flowers on a plant are perceived as bright red against the dim greenery of the leaves. With a weak illumination (the "realm" of rods), red flowers look duller, and the leaves seem to be more pale [8, 9]. It is interesting that measuring devices cannot detect this fine point, which directly influences the visual ability of drivers and pedestrians crossing a traffic way.

The reality is that with weak illumination, white or blue LSs provide relatively better visibility. Based on laboratory experiments and full-scale investigations, it was revealed [10] that white and yellow LSs at equal illuminance levels, as determined by measuring devices, influence vision differently. LSs with a bigger blue light component, considerably improve peripheral vision, as provided by rods, people feel calm and comfort, and adequately perceive their surroundings, which seems to be natural to them.

A conclusion from the above can be drawn, that a natural (daylight) illumination with high colour rendition reliability, gives clear spatial reference points [11].

It is also important to take into consideration that indications of measuring devices may not correspond to the requirements of standard illumination parameters, and besides it is unknown, to what extent these aspects of colour rendering are taken into account in artificial illuminating of pedestrian crossings. Illumination for the traffic to be safe as a whole includes maintenance of a sufficient back-

Fig. 2

Fig. 3

ground illumination level of the road surface so that objects (and potential obstacles) are visible for drivers as dark silhouettes (an effect of negative contrast) (Fig. 2). Negative contrast gives the best visibility of object outlines and should show object movement even at long distances, which is of critical importance for vehicle drivers. Human sight is especially sensitive to negative contrasts.

In positive contrast, an object is illuminated so that it looks brighter than its background (Fig. 3). This helps people to distinguish features of the object, for example, surface details and texture. This is important for object identification by drivers and therefore for pedestrian safety.

It is important to consider the overall rule that negative contrast, a dark silhouette against a light background, helps to detect the movement of an object, and the positive contrast, i.e. a light object against a dark background, helps decipher the object's details.

To ensure pedestrian safety and feeling of comfort, a combination of negative and positive contrasts should be used. The purpose and size of the pedestrian crossing determines whether near visibility is necessary, or whether distant visibility is sufficient alone to detect movement. Therefore, in places where pedestrians move within a limited space and along a certain way, the following approach is proposed: in immediate proximity from the pathway of pedestrian movement, a greater positive contrast should be provided by the illumination; further away, where detail accentuation is not necessary, the negative contrast should be created. This concerns a typical illumination of motor ways and streets using LDs with HPSLs.

The negative-contrast and positive-contrast illumination methods should be taken into consideration when developing systems of street, highway and pedestrian crossing illumination. The visibility of pedestrians who are on the traffic way or near it, whether stationary or moving, is a key safety requirement.

In theory, it is possible that a driver comes nearer to the pedestrian crossing, on which a pedestrian is standing, and the illuminated road surface makes the driver perceive the pedestrian as a dark silhouette due to the effect of the negative contrast. However much more often in reality, the car's headlights create the positive contrast effect. Under these circumstances, the positive and negative contrasts become equal, and the person on the pedestrian crossing becomes almost invisible or poorly distinguishable against the background (Fig. 4).

For this reason, national standards, for example European standard EN 13201–2:2003 and British standard BS 5489–1:2003, recommend using additional local illumination that ensures positive contrast under any road conditions. Illumination should warn drivers about the pedestrian crossing and make pedestrians visible as much as possible both on the pedestrian crossing itself, and on the adjoining pavement. In both cases, illumination should ensure their good visibility for drivers, and so provide pedestrian safety.

Fig. 4

When testing, the vertical illuminance on the road coating of the traffic way should be considerably higher than the horizontal. During measurement, it should be checked that drivers approaching the pedestrian crossing are not blinded by the illumination.

So, what is the real situation with pedestrian crossings illumination? Overwhelmingly in streets and on roads, energy efficient HPSLs are used as LSs in street luminaires. With their high luminous efficacy, approximate to light emitting diodes, long service life and low cost, HPSLs have many advantages as the most effective and economic alternative to the less effective and outdated HP mercury lamps (of MAL series and similar). However, HPSLs are absolutely unsuitable for illumination of pedestrian crossings: their yellow-orange light creates driver perception of pedestrians as dark silhouettes or shades without their clear identification as objects with hazard potential. This leads us to the simple conclusion that in order to increase safety on pedestrian crossings, it is necessary to analyse the mechanism of colour sight. It also means that white light illumination using LSs with MHLs or light-emitting diodes is needed for this type of illumination. At present, the latter more preferable: they are more durable, have more stable colour emission and are more energy efficient.

As stated above, today's streets, roads and especially pedestrian crossings are illuminated, if at all, by luminaires with HPSLs. This involves standard luminaires for road illumination. They mainly direct light longitudinally onto the roadway. As an example, Fig. 5 shows luminous intensity curves (LIC) for the most widespread luminaire for street illumination (ЖКУ-16 series of *Galad* Company production). This solution is perfectly suitable for road surface illumination but not for pedestrian crossings: light is distributed in equal parts to both sides of the luminaire along a large section of the road, instead of being concentrated within the pedestrian crossing. Half of light is not used practically, and the other half is not used optimally. It follows that to obtain a standardised illumination of a pedestrian crossing, it is necessary to use luminaires of at least twice the power or double the number[1].

So, what type of luminaire could provide a really high-quality, energy-efficient and economic illumination of a pedestrian crossings? We have established so far that the luminaire should have a white light-emitting diode LS and a special optical system ensuring illumination of the pedestrian crossing only, without light spill.

The advantages of such a luminaire compared to those widely applied today are as follows:

- Increase of pedestrian safety due through designing with vision activity in mind, and acknowledging the three-dimensional images of pedestrians:
- High energy efficiency;
- The number of luminaires required is reduced at least by half, also reducing the number of supports, cables, foundation and installation effort, as well as LD maintenance service cost;
- Complete avoidance of driver blinding effect due to directing the whole light along pedestrian movement pathways and creating a good vertical illuminance on the crossing.

There is a luminaire on the market today, which corresponds to all of the requirements listed above. This is a luminaire with light-emitting diodes and a patented optical system developed by *OSRAM* and *SITECO* companies, intended specifically for effective illumination of pedestrian crossings. It contains light-emitting diode modules installed in a facet op-

[1] Even in a recently published new concept of pedestrian crossing illumination developed by the Russian traffic police, an illumination system with four luminaires is used (Fig. 6).

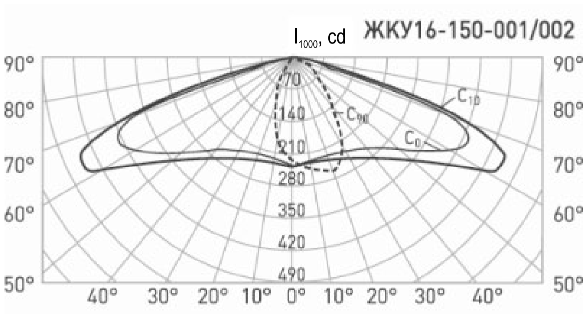

Fig. 5

Fig. 6

Fig. 7

Fig. 8

tical structure (i.e. consisting of many small specular elements) (Fig. 7). This structure is placed in a tight unit ensuring a high degree of protection of all optical elements from contamination and effective heat removal from the light-emitting diode modules. All of this ensures a service life of over 50 thousand hours, decreasing luminous flux to no less than 70 % of initial levels. An asymmetric optical system of the luminaire (Fig. 8) allows illuminating pedestrian crossings with controllable luminous flux and significant energy saving.

As it was noted above, the use of LDs with HPSLs for illumination of roadways is still optimal due to the specific features of night vision. At present, technology and energy efficiency of LDs with light emitting diodes do not suggest significant advantages over LDs with HPSLs in road lighting, either by energy savings, or by cost.

As an example, we present here a comparative analysis of LD costs for street illumination using luminaires produced by *Galad* Company (Fig. 5) and or 250 W HPSLs produced by *OSRAM* Company production. The first fig. in the lamp name represents the service life of the lamp before mass replacement, in years. For example, *2 Y* corresponds to two years, *3 Y* – to three years etc.. It is seen from Fig. 9 that after a ten year service life as determined by the standard requirements, LD cost lies in the interval of 5125 – 7050 rbl., maximum expenses correspond to the lamps with two-year replacement interval, and minimum – to the lamps with six-year interval. In this example, costs of the lamps themself and for their replacement are the only parameters considered; expenses for periodic optics cleaning and for electric power are not accounted for.

It is important to note that *3 Y* HPSLs are the most demanded in today's market. These are used by organisations operating accurately and carefully because they understand the real operating problems, not simply absorbing investments. At the same time, a great number of tenders for HPSLs, are driven only by the cost aspect, driving users to the cheapest HPSL *2 Y* solutions for the initial installation, and as a consequence, the least cost-effective solution on LD possession is selected without taking into consideration economic factors. The most ex-

Table 1.

Name	Rated power, W	Rated luminous flux, lm	Rated efficiency lm/W	Time between failures 5% (B5), hours	Average life-time (B50), hours	Socket	Max. Length, mm	Diameter, mm
NAV-E 70W SUPER 6Y	70	6 300	90	24,000	40,000	E27	152	71
NAV-T 70W SUPER 6Y	70	6 600	93	24,000	40,000	E27	152	39
NAV-E 100W SUPER 6Y	100	10 400	104	24,000	40,000	E40	152	71
NAV-T 100W SUPER 6Y	100	10 700	107	24,000	40,000	E40	210	47
NAV-E 150W SUPER 6Y	150	17 000	112	24,000	40,000	E40	226	91
NAV-T 150W SUPER 6Y	150	17 500	115	24,000	48,000	E40	210	47
NAV-T 250W SUPER 6Y	250	33 200	130	24,000	48,000	E40	257	47
NAV-T 400W SUPER 6Y	400	56 500	141	24,000	48,000	E40	285	47
NAV-T 600W SUPER 6Y	400	90 000	151	24,000	48,000	E40	285	47

pensive lamp for initial installation is the newest *6 Y* HPSLs. However, within 2.5 years of operation the costs are comparable with the cheapest solution, and over their entire service life, these LDs ensure saving of almost 30 % (Fig. 9).

At the same time, it appears that there are no economic benefits of the light-emitting diode alternative. A luminaire with light-emitting diodes from the medium price range, with luminous flux the same as that of a luminaire with HPSLs of 250 W power, will be more expensive in operation, specifically 2.8 times more than a luminaire with *2 Y* HPSLs, and 3.9 times more expensive than with *6 Y* HPSLs. For information, Table 1 contains technical data of new

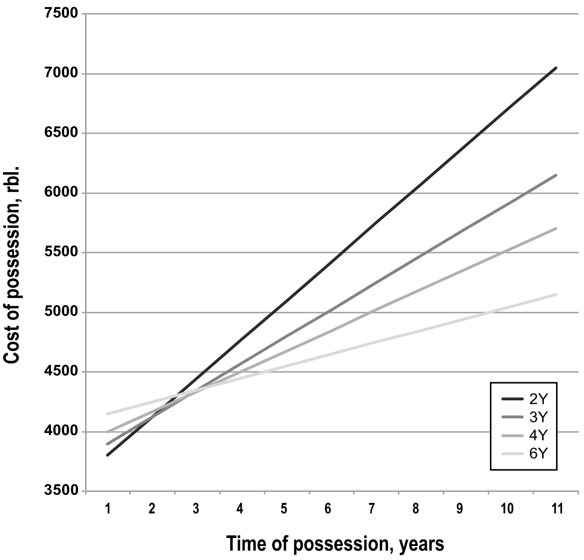

Fig. 9

HPSL *6 Y* generation (*OSRAM*) with a raised luminous efficacy and service life.

CONCLUSION

- For illumination of highways, motorways and streets with a high and middle traffic intensity, use of LDs is optimum with high-quality luminaires manufactured of high reflecting materials in combination with high-efficiency HPSLs of the last generations. They generate the minimum operation maintenance expenses during the entire LD service life, and not just at the beginning of their operation.
- Additional energy savings, of approximately 15 %, can be achieved when using electron ballasts. And if the function of the decreased power (dimming) is used in night-time, when traffic intensity reduces considerably, energy saving of up to 40 % can be reached: exactly this amount of power decrease is possible with the *6 Y* HPSLs (*OSRAM*).
- For the illumination of pedestrian crossings, use of specialised luminaires with light-emitting diodes is optimal. These luminaires ensure fewer lighting installations necessary and improve three-dimensional object recognition. In this way, maximum pedestrian safety can be achieved. For the sake of safety, the economic aspect of light-emitting diode illumination systems pales into insignificance, giving place to safety considerations (for very understandable reasons). Moreover, it should be clear that light-emitting diode systems are a result of considerable investments in their development, they represent unique engineering solutions, use high production technologies and know-hows. Consequently, they cannot be objectively considered as a cheap product of mass application, which is often expected from the "light-emitting diode revolution".

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POLYCHROME SPECTRALLY CHANGEABLE ILLUMINATION DEVICES WITH LIGHT EMITTING DIODES: EXPERIENCE OF DEVELOPMENT AND APPLICATION

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ABSTRACT

The main aspects of theory, structure and technology are considered for illumination devices on the *RGB-mixture* principle with light emitting diodes admitting a spectrum of radiation (colour) dynamic control. A possibility of synthesis of wide colour range, including white light in the interval of correlated chromatic temperatures T_c = 2000–10000 K, is shown at high special colour rendering indices $R_1 – R_{14}$. Versions of implementation of such controllable devices for different applications are presented (general purpose illumination, operational room illumination and special illumination for correction of psychophysiological state of a person).

Keywords: illumination device**,** light emitting diode, *RGB- mixture*, colour rendering index, T_c, dynamic control, spectrum control

INTRODUCTION

An essential trend of light emitting diode (LED) illumination during the last years is the changing focus from quantitative indicators (luminous efficacy and luminous flux) to qualitative parameters of the generated light. In fact, the success reached in increasing the luminous efficacy of white LEDs is impressive: for February 2013, the record for laboratory samples has shown 276 lm/W, and for serial ones, it has approached a level of 200 lm/W [1, 2]. The results close to the theoretical limit of 283 lm/W [3] give evidence of a high perfection degree of the structure and technology of the white LEDs based on dark blue *AlInGaN* radiating crystals with phosphor radiation conversion. It should be noted, that ten years ago, optimistic luminous efficacy forecasts for LEDs amounted to 60–80 lm/W. In this new context, when world leading manufacturers *Nichia*, *Cree*, *Philips Lumileds* and *Osram* have reached an approximately identical very high luminous efficacy level, quality indicators of the generated light play a critical role in competition. In he frame of illumination, there is a possibility to reach a wide interval T_c = 2700–6500 K with support of high colour rendering indices [4]. To meet the latest requirements for high quality illumination, general colour rendering index R_a and special colour rendering indices $R_8 – R_{14}$ should be ≥ 95 and 85 respectively [5]. Finally, a new and possibly the major illumination quality is its controllability that is a possibility to change in the operation process spectrally-and-colour parameters of illumination devices (LD). It is generally recognized already that most interesting prospectives of such “intellectual” (or “smart”) light are connected with a possibility to render a positive influence on psychophysiological and general physical health of a person, or in other words, to create an optimum light medium for vital activity [6, 7]. The controllability degree can be different: from T_c time variation to reproduction of a wide colour range of the natural colours including millions of colour shades.

On the whole, the problem of development of spectrally changeable LDs with LEDs is an integrated task which includes:

• Theoretical aspect; the simulation of colour mixing processes, substantiation of an optimum selection of initial LEDs by spectra to receive white light with a preset T_c and colour rendering indices, or chromatic light determined by specific applications.

• Structural and technological aspects, the broadest and most multi-dimensional; the development of technology and structure of the LED itself and of the polychrome multicrystal LED modules, secondary optics, heat removal and so on.

• Circuit and program aspects; the development of electronic units and of software for radiation control by spectral composition and by intensity according to set algorithms.

In the following section we will consider these aspects using development examples in some detail from work at the Scientific and Technological Center of Microelectronics and Submicron Heterostructures of the Russian Academy of Sciences during 2008–2013.

COLOUR MIXING OPTIMISATION: COMPUTER MODELLING AND EXPERIMENTAL RESEARCH

Issues associated with colour mixing optimisation to obtain white light at set T_c and an optimum compromise between luminous efficacy and colour rendition quality as applied to LEDs, were investigated in detail during the last decade, beginning from early works [8–10] and to the latest Russian publications [11, 12]. One of the main results obtained consists in the fact that at a typical LED spectra half width $\Delta\lambda_{0.5} \approx$ 15–40 nm, obtaining white light at general colour rendering index $R_a > 95$ demands addition of uniformly enough distributed spectra in visible interval of four or five LEDs with peak wave lengths λ_{max}. A further, more dense filling of the spectrum of absolutely black body (ABB) due to the LED number increasing, hardly anything adds to R_a value but leads to essential losses of luminous efficacy and to the system complication. At the same time, even a small deviation of separate LED λ_{max} from optimum values, can lead to a sharp decrease of separate colour rendering indices, especially of $R_8 - R_{14}$. Use of phosphor LEDs with a wider spectrum, D$\lambda_{0.5} \approx$ 70–100 nm for colour mixing, naturally facilitates the problem.

To solve the problem of mixing LED spectra, a numerical model developed by SOFT-IMPACT LL Company was used. This model has allowed finding the optimum according to a set objective function when varying a great number of mixing parameters. Experimental LED spectra based on *AlInGaN*, *AlGaInP* and on phosphor LEDs are approximated by suitable functional dependences. In the colour mixing optimisation process, λ_{max} of different LEDs and their multispectral power portions are varied in total radiation. Herewith, at the first stage of the theoretical simulation it was supposed that mixing of radiations of the different light sources was not limited to technical abilities (real efficiencies or luminous efficacies of light sources were taken into consideration later). As a result of the variation, a total spectrum of the combined light source was found, and its analysis was carried out, that is chromaticity coordinates x and y, T_c, R_a, as well as $R_1 - R_{14}$, and luminous efficiency were found. The model allows forming multi- parameter target function and optimising white light in accordance with set T_c or with R_a, or with luminous efficiency. As additional parameters can be applied, such as maximum deviation of chromaticity coordinates from ABB line, a limit bottom value of any $R_1 - R_{14}$ indices, as well as other restrictions. The developed algorithms provide working capacity of the model for a great number of varied parameters. Simulation of polychrome LED light sources was carried out both for phosphor-free versions using LEDs based on *AlInGaN* and *AlGaInP* hetero-structures, and for a "hybrid" version with phosphor and phosphor-free LEDs.

Along with the simulation, at wide coverage of initial λ_{max} and $\Delta\lambda_{0.5}$ spectra, experimental researches show that for synthesis of high-quality white light with T_c = 2500–10000 K, the optimum set is a set of six spectral bands of phosphor-free LEDs: four of them are based on *AlInGaN*[2] ([1]460/22, 490/30, 520/34 and 560/42 nm), and two are based on *AlGaInP* (595/18 and 630/15 nm), where experimental values of λ_{max} and $\Delta\lambda_{0.5}$ are specified using slash. Spectral distributions and colour coordinates for the LEDs chosen are shown in Fig. 1. In this case, addition of the four bands is sufficient for each specific T_c. The choice of the six-colour LED module is based on the intention to raise its universality due

[1] Corresponding *AlInGaN* emitting hetero-structures were grown up in the Scientific and Technological Center of Microelectronics and Submicron Hetero-structures of the Russian Academy of Sciences together with the FTI of A.F. Ioffe of the Russian Academy of Sciences.

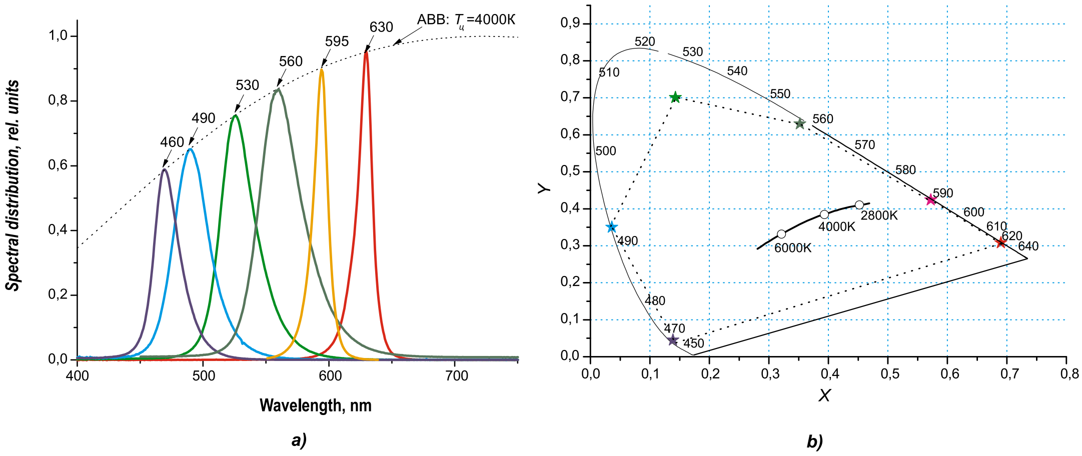

Fig. 1. Spectra of six light emitting diodes used for colour mixing (envelope curve – ABB spectrum with $T_{c} =$ 4000 K), (a) and chromaticity coordinates of these light emitting diodes on the CIE 1931 colour diagram (b)

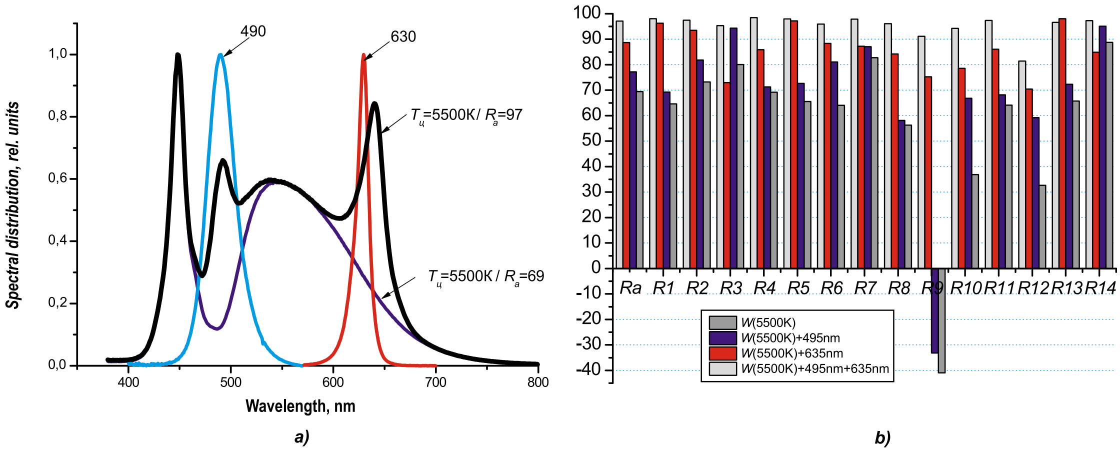

Fig. 2. Spectra (a) and colour rendering indices R_a and R_i (b) of white LED with T_c = 3200 K based on a phosphor white light emitting diode with additional correction using phosphor-free light emitting diodes with λ_{max} = 490 and 630 nm

to overlapping a wide T_c interval and accentuation of some colours for special illumination conditions (microscopy, surgery, museums, etc.).

In another version of a white light source implementation, mixing of two phosphor-free LED spectra was used: 490/30 and 630/15 nm with a spectrum of phosphor LED (cold-white, 5500 K). The spectra are shown in Fig. 2 a. As an example, Fig. 2 b illustrates abilities of R_a and $R_1 – R_{14}$ increase when adding spectral components. It is well seen that spectrum correction of a standard phosphor LED due to addition of blue-green (λ_{max} = 490 nm) and red (630 nm) spectral bands allows raising R_a from 69 to 97. A sharp increase of R_9 from negative values to 91.15 and of R_{13} from 65.7 to 96.6 is especially important (these values are not taken into consideration when calculating R_a but they play an essential role when reproducing colours of biological tissues and of skin). The obtained results are well in line with the design data and have provided development of LDs with LEDs meeting high requirements of colour reproduction.

EXAMPLES OF DEVELOPING POLYCHROME SPECTRALLY CHANGEABLE LDS WITH LIGHT EMITTING DIODES

We have already noted that spectrally changeable LDs with LEDs are complex devices requiring several considerations, including the following:

- Selection of the LED element base, designing multi-element modules (matrices) with a dense LED assembly, individual electric “commutation” and effective heat removal;
- Development of an optical system ensuring a high transmission factor, a set spatial distribution of luminous intensity and angular uniformity of colour parameters;

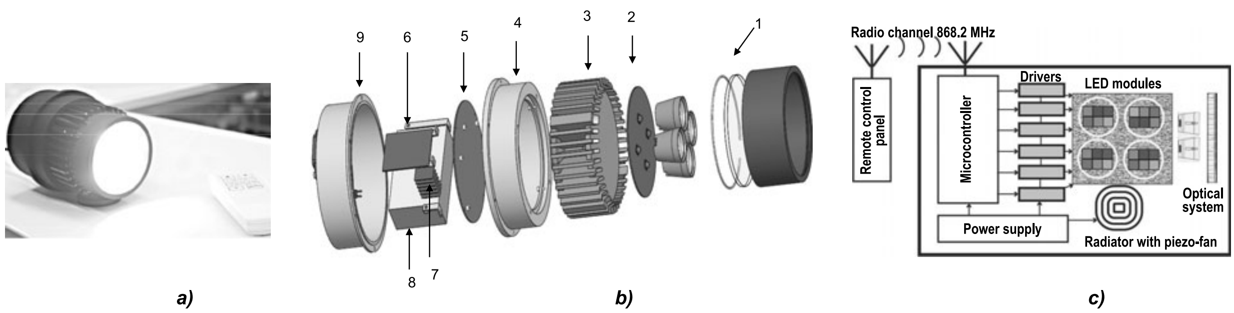

Fig. 3. General view (a), schematic view of the main units (b) and CLEDLD electric flow chart (c): 1 – optical system, 2 –light-emitting diode module, 3 – radiator with pieso-fan, 4 – case, 5 – microprocessor board, 6 –antenna unit of radio channel, 7 – power supply drivers for LED modules, 8 – power supply, 9 – case cover

• Development of control circuits and electronic units including power supply, microprocessor, ballast, feedback sensors, control data transmission radio channel, control panel or computer and software.

The following example illustrates approaches to the challenges above. The development of a controllable polychrome LD with LEDs for general purpose illumination (CLEDLD) made as part of the State contract with the Ministry of Education and Science dated 04.06.2012 #12.527.12.5006. The CLEDLD is intended for illumination of inhabited and production rooms, primarily of those, which are objects of increased requirements for quality of light medium (nurseries and medical institutions, museums, textile and jewelry production, autonomous objects etc.). The main requirement is illumination with T_c (± 100 K) = 2700, 3500, 4000, 5000, 5700 and 6500 K and $R_a > 90$. The LD should be distantly controlled and ensure receiving and transmission of the following radio command signals from a remote control: 1) switching on/off; 2) T_c set according to the above values; 3) luminous flux set from 0 to 100% with discreteness of 10%.

The radio channel parameters are: frequency interval from 868.7 to 869.2 MHz; Manchester code; remote control response time ≤ 1 s; operation range is 30 m.

A picture of the CLEDLD with remote control and CLEDLD general structure are shown in Fig. 3. The optical system, the calculation and optimisation of which were carried out with the *Zemax* program, includes three elements: a lens with refracting inner surface and reflecting external surface (due to full inner reflection) (the manufacturer is *Ledil* company) and two microprismatic diffusers. The system has radiation angle of 2 $Q_{0.5} > 100$ º and a high angular uniformity of colour parameters.

The key CLEDLD element is a polychrome LED module. The modern LED industry (non-domestic) suggests a wide range of three and four monochrome energy-effective high power LEDs as an element base for polychrome LDs with LEDs. Among the best series of such LEDs are: *XLamp XM-L Colour* and *XLamp MC-E Colour* (*Cree*), *LZ4–00 MA10* and *LZ4–04 MDCA* (*LedEngin*) and *CBM-380* (*Luminus*). These were used in previous studies [13, 14]. Their main advantage at the moment is maximum energy characteristics, and the main disadvantage is an incomplete colour range. These are either *RGBA* or *RGBW* radiators, where *R*, *G*, *B*, *A* are monochrome red (630 nm), green (520 nm), dark-blue (460 nm) and yellow (590 nm) LEDs, and *W* are phosphor LEDs of cold-white ($T_c \approx 6500$ K) or of neutral-white (4000 K) light. To overcome the specified limitation and to develop effective radiators for "insufficient" wave lengths, the Scientific and technological center of microelectronics and submicronic hetero-structures of the Russian Academy of Sciences (RAS) together with the FTI of A.F. Ioffe of the RAS intensely carries out research into growth technologies of emitting hetero-structures in the *AlInGaN* system. Hetero-structures of dark-blue + dark-blue-green types (460 + 490 nm), dark-blue + deep green (460 + 560 nm), etc. [15, 16] were developed. These are LED versions necessary to achieve high colour rendering indices but absent from the market. Experimental models of such emitting crystals are used in our six-colour LED module. Its spectral composition is presented in Fig. 1 a, and its picture is shown in Fig. 4 in comparison with known industrial samples of *LZ4–04 MDCA* series (*Led Engin*) and *XLamp XM-L Colour* series (*Cree*). In total, four six-colours LED modules connected in series are involved into the CLEDLD.

a) b) c)

Fig. 4. General view of multicrystal polychrome light emitting diodes of LZ4–04 MDCA series (Led Engin) (a), XLamp XM-L Colour series (Cree) (b) and own development for the CLEDLD (c)

The following section will briefly consider the electronic components. The board of the central processor should ensure command signal receiving from the radio module, control the ballast according to the signals and switch on/off the operating mode. To unify the product, microcircuit *C1110 FX* is used as a basic element of the central processor board. The circuit with a radio channel in the received-transmitted mode is also used in the control panel. The central processor of this microcircuit has a wide range of abilities allowing to reach the main goals of the CLEDLD control. To change the luminous flux, the pump current pulse-width modulation method (PWM) was used. This method provides linear dependence of luminous flux in a wide dynamic current interval. Microcircuits *MAX16819* with output power more than 25 W were used as ballasts. The PWM relative pulse duration control interval amounted to 0–100 s, PWM frequency was equal to 10 kHz. The power supply unit includes two sources: operative and standby (waiting mode with a low energy consumption, which cannot be disconnected by the user). Effective cooling of the LED module was carried out by a radiator with piezo-fan (*Synjet* Company).

The above described LD was developed as universal enough, designed for a wide application in general purpose illumination or to illuminate separate objects at exhibitions, in show cases etc. [17].

Before, we had developed some versions of specialised spectrally changeable medical purpose LDs. One of them is an operational luminaire allowing to synthesize not only cold-white or warm-white light, but also preset chromatic narrow-band light for contrast visualization of biological tissues [14]. With light incidence on a biological tissue, a part of the light is reflected by the tissue surface, a part is diffused, and a part is absorbed. The reflected light comes to the eye of the surgeon, and in case of accommodation of the luminaire spectrum with the spectral reflection factor curve, one can have a strong reflected signal, and in case of mismatch, on the contrary, it will be almost a black background. This approach essentially underlies the spectrally changeable operational luminaire, which we have proposed. To make a distinction of some biological tissues against others, the surgeon selects the colour (spectrum) of the changeable luminaire, with which necessary sections of the operational field being objects of the current manipulations become contrast against other tissues. Clearly this method, which allows distinguishing in real time any differing normal tissues of various morphological structures and revealing focal points of a pathological histogenesis without long preparation, could be needed in many branches of medicine and can improve treatment results of malignant neoplasms and other surgical pathologies.

As the operational luminaire base, a single super high power quadric colour *RGBW LED* of *CBM-360* series (*Luminus Devices* Company *Inc*) was used. The LED represents an electronic micro assembly including emitting crystals of a large area (9–12 mm^2) mounted in a heat-conducting case, so that input electric power of the radiator could reach 100 W, and output luminous flux surpasses 4000 lm. One feature of the operational luminaire is its rigid requirements to the light spot both concerning illuminance (> 10000 lx), and by colour uniformity. To meet these requirements, we have developed original optical system, including a prismatic concentrator and a triplet projective lens. The structure of the main luminaire units and optical system are shown in Fig. 5. Control of the light parameters at the preliminary calibration and luminaire adjustment stage is carried out from a distant computer using specially developed software. The correspondent interface allows to easily select colour characteristics and time changing colour and intensity of the radiation according to the set algorithm. In practice, control (choice and adjustment of the spectrally colour mode) is carried out by the surgeon or surgical as-

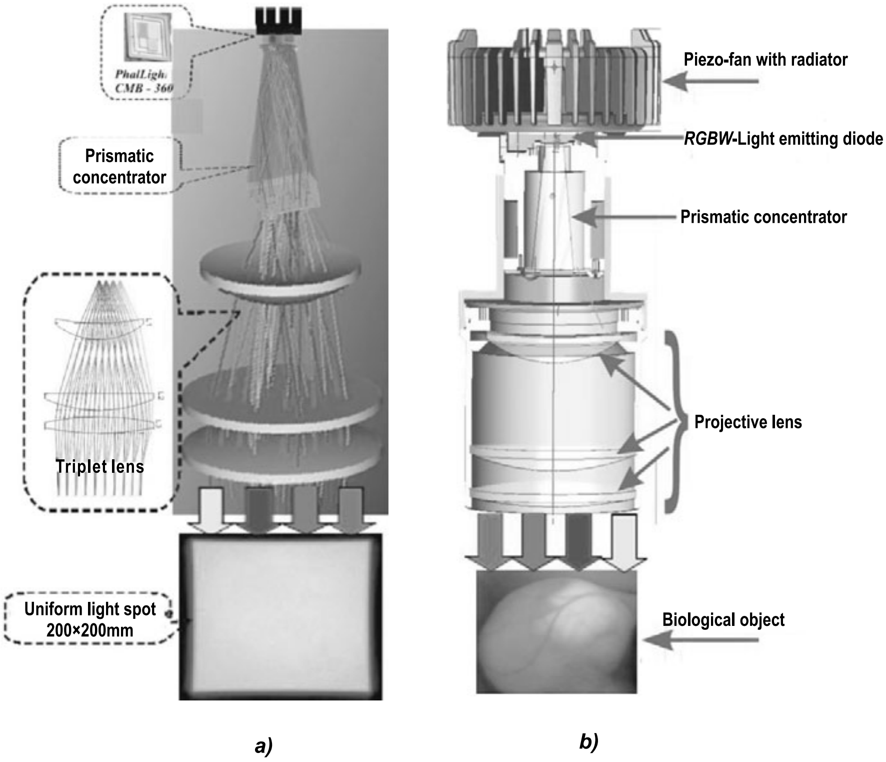

Fig. 5. Optical system (a) and structural view of main units (b) of the operational luminaire

sistant from a push-button panel connected with the luminaire through *Bluetooth* radio interface of class two with the range up to 30 m. The *Bluetooth* controller supports the *RFCOMM* protocol of sequential exchange.

Another version of the spectrally changeable LD with LEDs has been developed for a hard-software medical-and-biologic system in order to determine and correct psychophysiological and functional state of operators working in extreme conditions (dispatchers, pilots, crews of autonomous objects, etc.), as well as of people with some mental disorders [6, 18, 19]. Functionally the system allows recording state of a person on a wide range of parameters synchronously with change of parameters of the light influence: electroencephalogram (EEG), electrocardiogram, frequency of breath and psychological tests. The ultimate goal of this is development of illumination algorithms, which would promote activation (attention concentration, reaction speed) or, on the contrary, relaxation (rest and recovery) of the operator during set time intervals.

The main characteristics of the developed LD are as follows: 1) the output luminous flux is up to 10000 lm, which is enough not only for local but also for general illumination (rooms); 2) area of the synthesised chromaticities amounts to more than 75 % of the area outlined by the locus on the colour CIE 1931 diagram; 3) T_c interval for white light amounts to 2500–12000 K with R_a = 70–90; 4) wide distribution of luminous intensity in case of angular uniformity of radiation chromaticity.

Structurally, the LD unites in a single case a matrix of high power $R - G - B -$ and A-radiating crystals (144 in total) connected into series-parallel groups, and a power supply circuit containing boards of processor, ballast, of power supply unit and of transceiver of radio channel for data exchange with a master computer. The differences from the above described CLEDLD are luminous body configuration (a big rectangular screen of a moderated luminance) and control (from a computer) so that the correspondent interface allows setting colour and luminance parameters and time for changing them by a broad set of algorithms. In a special window of the display, current colour and luminous flux are shown. LD general view and interface built in the hard-software medical system, are shown in Fig. 6.

As the research result used a large statistical sample, it was found that white light with $T_c \approx$ 3800, 4800 and 7000 K does not influence significantly the spectral characteristics of the main rhythms of EEG. And white light with $T_c \approx$ 1700 K and in a greater measure with $T_c \approx$ 10000 K, on the contrary,

Fig. 6. Hard-software medical system based on spectrally changeable illumination device (LD): a – computer with control interface 1 and spectrally changeable LD 2; b – module of objective medical control: electroencephalograph 3, psychological tests 4, electrocardiograph 5, detector of breath frequency 6 and detector of arterial pressure 7

is physiologically active, because it leads to changes of spectral power of $\alpha - \theta$ – and δ – rhythms of EEG. Two main types of the light influence are accentuated: relaxing and activating. The obtained data allow carrying out a selection of optimum illumination for household and public rooms, as well as using spectrally changeable LDs for individual correction of psychophysiological state of a person.

CONCLUSION

Colour-dynamically controlled LDs with LEDs for different fields of application are developed. They allow synthesizing either white light in a wide T_c interval, or chromatic radiation of different chromaticity. Such LDs are of a great interest both for general purpose illumination, and for special illumination (architectural, artistic, surgical, in microscopy, in phototherapy, for correction of psychophysiological state of a person, for agricultural technology, etc.).

Different LD structures with LEDs, including electronic control units and software are considered, and their influence on the output characteristics and control abilities are studied. Several model samples of the controlled LDs both for general purpose illumination, and for medical and biologic applications are created.

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TECHNOLOGICAL SOLUTIONS FOR SERIAL PRODUCTION OF LIGHT EMITTING DIODES

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ABSTRACT

A short description of the technological process of light emitting diode assembly is given. The main technological operations are described separately, the main problems arising during technology development and its launching into manufacture are considered. Special attention is given to selection of the process equipment, to the degree of process automation and to the controllable parameters.

Keywords: light emitting diode, light emitting diode assemblage, assemblage technology, serial production

Currently, the urgency and importance of light emitting diode illumination is undoubtable. On the illumination market, light emitting diodes (LED) and luminaires with LEDs represent revolutionary new light sources ensuring both essential electric power saving, and fundamentally new light quality, as well as efficiency of illumination systems. In Russian and foreign professional publications, many papers on the subject of LED structure, power supplies, phosphor properties, application examples, etc. have been published. However, very few studies have addressed the problems of LED manufacturing technology. In this article, we have tried to in part close the gap.

The methods described are based on experience of serial LED production in the Svetlana-optoelectronics Company group. The paper is structured as follows: a general description of the LED assemblage technology is given, its main operations are considered, typical technological problems of LED production process are discussed, adressing:

- Process automation degree;
- Process equipment selection;
- Development of the control programs and determination of the controllable process parameters;
- Technological preparation of the production.

The main technological processes implemented for assembling LEDs manufactured with the *SVETLED*® trade mark, are presented in Fig. 1.

The process begins from **surface preparation** for the operation of component assemblage onto the LED case. The primary goal at this stage is surface cleaning. Plasma cleaning of the cases using high-frequency discharge within the atmosphere of the process gas (for example, argon or oxygen) allows removing contaminations from the coating surface, thus improving adhesion of the glue between component and case.

When selecting equipment for ionic-plasma cleaning (Fig. 2), depending on the task at hand, one should determine the required volume of the working chamber, the power and frequency of the plasma generator and the usage demand for several working gas mixtures. At the start of the production cycle, and in the case of a wide product range, it is better to use chamber type models with manual loading and unloading of group work pieces, which does not demand the individual technological equipment. Control programs should contain the following controllable parameters: working gas pressure, cycle duration and generator power.

Components mounting to the case involves deposition of the junction material and the component installation.

One of the main technological questions when implementing this process in production is the choice of deposition method. Here, accuracy and reproducibility on the one hand, and productivity on the other, are essential criteria for serial production. There are several methods for transporting the joining material: printing, dosage and screen printing. The choice is influenced by the joining material, component size and group workpiece size.

For components of less than 500×500 µ size, using joining material with filler particle size of more than 20 µ, optimal process reproducibility is ensured with printing as the transport method for joining material. The process has the following controllable parameters: the profile of the printing tool movement, rotation speed of the junction material bowl, overrun value and tool pressure, delay time of the printing tool and depth of its dipping into the bowl.

The method of material deposition using dosage is less accurate but more productive. This method should be used for components greater that 1500×1500 µ in size. A stable result can also be obtained by joining material dosage without filler when using dosage for components from 500×500 µ. During this process, it is necessary to control the pressure and supply time, as well as to trace consumption of the dosed material. A significant aspect of process stability is the optimum choice of diameter and material of the dispenser needle. If choosing this method, the significant consumption of expendable equipment parts should be accounted for.

Using a weighing system of the dose provides automatic control of its volume and helps to avoid decreasing quality because of changes to material. An automatic system for needle cleaning allows for continuous operation of the dosing unit and of its productivity.

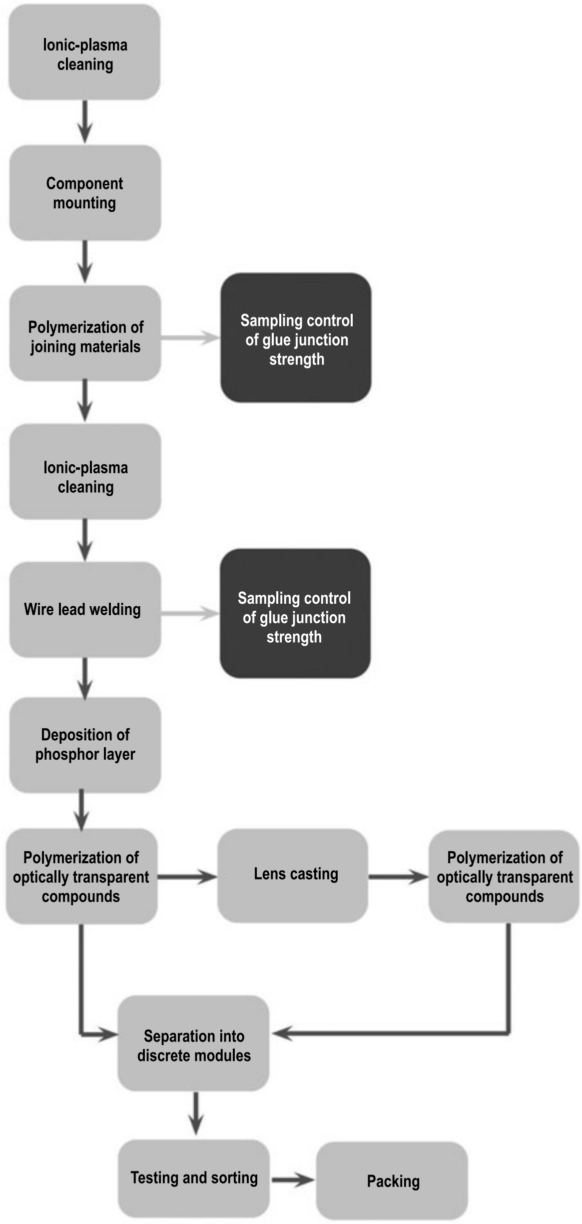


Fig. 1. Technological diagram of the production process for white colour radiating LEDs

Fig. 2. Ionic-plasma cleaning unit

Fig. 3. The stencil process printer

Fig. 5. Chamber type dryer

The most productive but least exact method is screen printing.

Typical accuracy of printers for screen printing (Fig. 3) does not exceed ± 30 μ. In order to increase the accuracy, expensive solutions are required. Using the *Look Up/Look Down* double chamber and an automatic device for the screen printing stencil, as well as for group workpiece alignment, allows for quicker and more exact combination of reference signs of the group workpiece and stencil. A self-leveled squeegee with programmable speed and travel distance, as well as real time closed pressure control system ensures split-hair accuracy of the printing. A system of raster imaging allows making fast *2-D* process control. In case of parameter discrepancy with the preset values, the system can clean the stencil, add the material and give an interference signal to the operator. A combined use of the above provides accuracy increases of up to ± 12.5 μ. A high-grade automatic stencil cleaning from the bottom increases non-stop operation time of the printer and its productivity.

In view of essential technological losses, the applied material range is limited in practice by soldering pastes and fluxes.

The stencil printing method implies more expensive production preparation. Besides a vacuum adapter, which is separate for each group workpiece type, nickel stencils of 30 to 60 μ thickness must be manufactured. The stencils should be made using the electrotyping method, which guarantees a maxi-

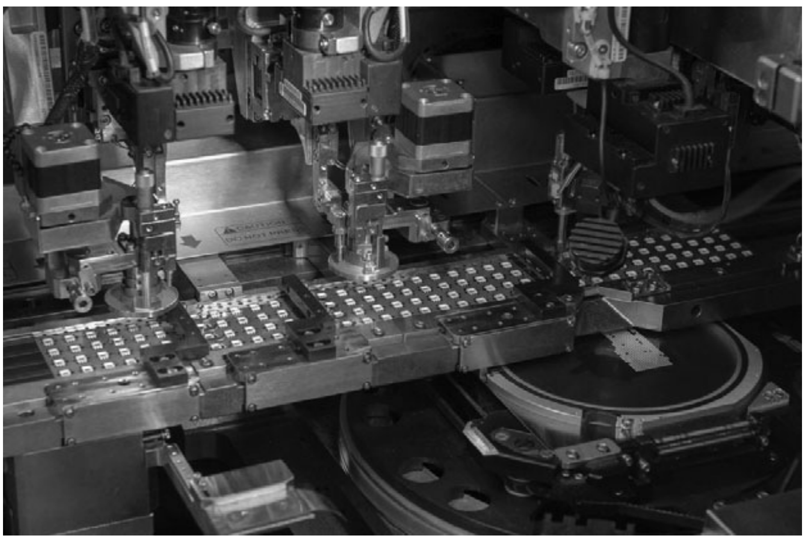


Fig. 4. Deposition of joining material by printing and crystal mounting

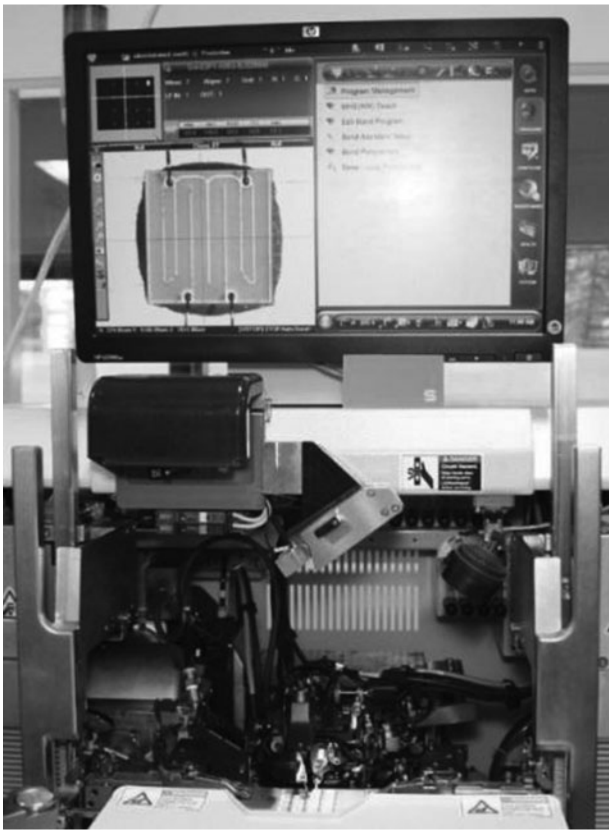


Fig. 6. Wire leads forming unit

mum difference of the aperture sizes within ± 3 μ. Depending on product output volume, a various degrees of automation for the loading and unloading of group workpieces can be used, equipment change duration can be optimised, and equipment cost can be reduced.

The stencil printing method is efficient for large dimension group workpieces. One of the advantages of this method is the possibility to deposit the joining material under components of flip-chip structures. A

Fig. 7. Microwelding unit working area

disadvantage is that it is impossible to combine material deposition and component mounting operations within a single installation.

Modern automated equipment for component mounting is equipped with the main axis for component installation and with one or two auxiliary axes with equipment for deposition of joining materials: dispenser and/or stamp or two units for printing (Fig. 4). On the installation auxiliary axis/axes, joining material dosage occurs onto the group workpieces at the point of component installation. After the operation finishes, the group workpiece is delivered to the main installation axis by means of a transport system, and then the placement head delivers a component to the group workpiece joining point, and the component is installed using a programmable force. The process is simultaneously performed on the main and auxiliary installation axes.

During mass production, a maximum degree of automation is needed. This is provided by a con-

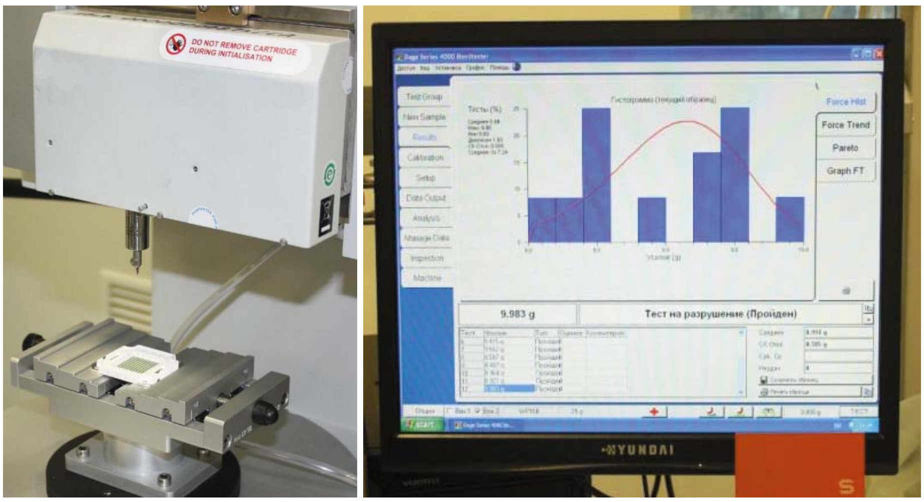


Fig. 8. Testing welded junctions

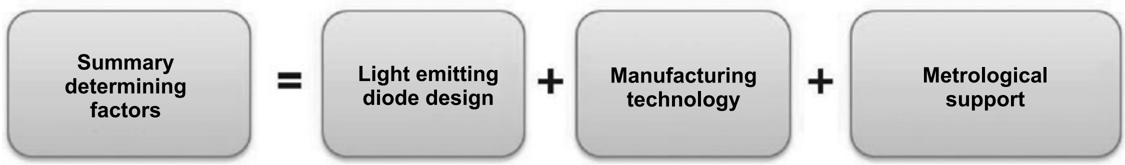
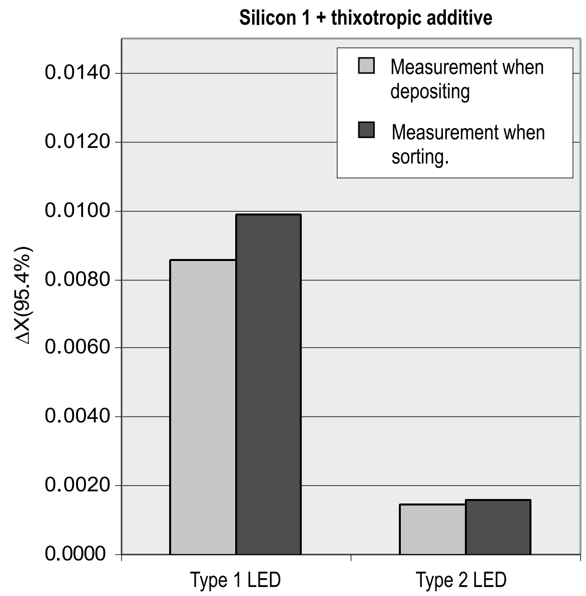


Fig. 9. Major factors influencing product colour characteristics



	Case type	Power, W	Number of crystals, pieces
Type 1 LED	*top view*	1	1
Type 2 LED	*top view*	1	6

Fig. 10. Comparative diagram of chromaticity coordinate reproducibility for different light emitting diodes of different structure

veyor system equipped with input and output buffers for feed chutes, which allow group workpieces moving in automatically within the operation area, where they are fixed by vacuum or mechanical clips; by a system of the component feed magazine control, which automatically delivers components to the pusher module and replaces plates with components, as well as automatic calibration and replaceable tools. A turnaround system of component pushers ensures a high efficiency, and the possibility to manufacture a wide range of products. Duration of the dry cycle is less than 200 ms. Accuracy of the equipment for component mounting is on average equal to ± (30 ÷ 40) μ. This accuracy is insufficient for some applications. Technological facilities in this case can be equipped with additional options. For example, video cameras, which help to recognize reference marks on the group workpieces and to automatically calculate coordinate deviation and turn angle of the basic module on every group workpiece; calibration after a component capture by means of the video camera; quality control performed immediately after termination of installation with programmed allowance and inspection intervals; quadric-colour illumination of the process operation area leads to installation accuracy of to ± 10 μ.

The following control parameters guarantee the stability of the process: overrun value, pusher needle moving speed, delay time for a component detachment, moving speed of the placement head, level of vacuum at the placement head.

The process demands for a precise technological equipment such as individual adapters and feed magazines for each case type.

For the polymerization of joining materials, dryers are required. There are chamber and conveyor type dryers. Using conveyor-based dryers is only efficient in high volume manufacturing of a limited range of products. When choosing a chamber type dryer (Fig. 5), the process engineer should take into consideration a chamber size, number of chambers, number of temperature controllers, drying temperature and accuracy of temperature maintenance. The size of the operation area is determined by the required productivity and by the dimensions of the group workpieces. Splitting the dryer into several chambers equipped with individual temperature controllers allows unifying the equipment and spreading the functionality of temperature profile development. Stability of the drying conditions is ensured by means of convection heating. To prevent the oxidation of bonding pads for welding and soldering, drying is carried out in a protected atmosphere. The recommended drying modes are specified by the manufacturer's specification. When implementing the process within a real production, the process engineer visually determines whether polymerization is full or not using a microscope and special **testing equipment**. To perform a destructive test of the glue junction, a special cartridge with a fixed tool is used. The test results, obtained data and their per-

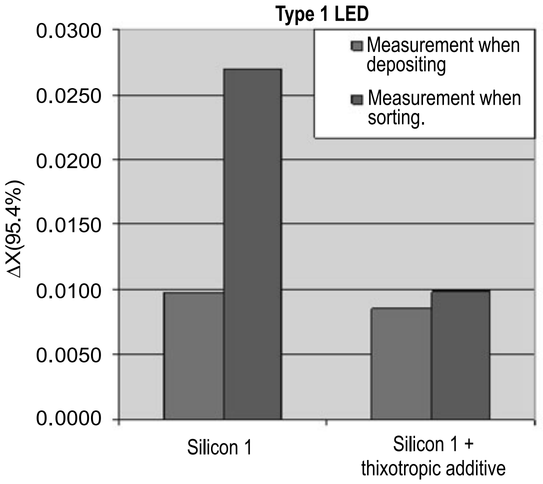


Fig. 11. Change of chromaticity coordinate dispersion for light emitting diodes when changing thixotropic properties of a silicone compound

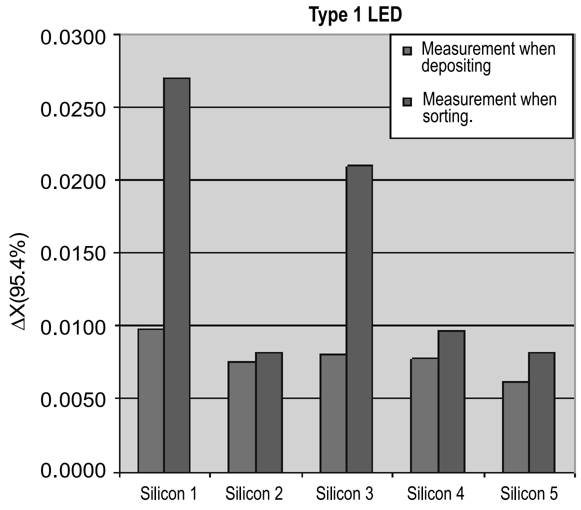


Fig. 12 Influence of silicone properties on dispersion of chromaticity coordinates

formance against international standards, for example of *MIL 883*, is recorded. Then a decision is made regarding the need for corrections within the process parameters.

To create a high-quality welded joint on certain surface types, for example, E*NIG*, **primary surface preparation** is made using the high-frequency discharge treatment method in an argon atmosphere. When selecting equipment for ionic-plasma cleaning, the conveyor-based method should be used in this part of the production process, or the method of automated loading-unloading workpieces of the shuttle type.

To form the wire leads from crystals to the light emitting diode case, the process of ultrasonic microwelding is applied. The process of ultrasonic microwelding is based on introducing transformed ultrasonic oscillations into the junction area without considerable plastic strain of welded elements. There are two types of weld: "ball-wedge" and "wedge-wedge". Gold and aluminum wires or ribbons are used most often. Silver or copper are rarer. The equipment, which is manufactured for microwelding process (Fig. 6), operates with 17 ÷ 75 μ diameter wires. The 20 ÷ 32 μ interval is most useable. The product structure determines the selection of microwelding material and conductor diameter.

When selecting the welding equipment, one should take into consideration the size of the operation area, generator power, productivity and travel of the converter along *Z* axis, as well as determine heating area number and degree of automation when loading and unloading group workpieces. It is necessary to apply precise technological equipment, which unambiguously positions and reliably fixes the group workpiece in the operation area (Fig. 7).

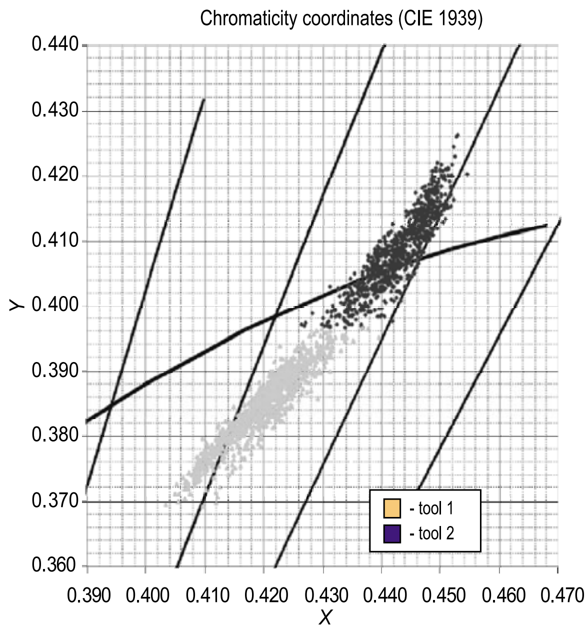


Fig. 13. LED chromaticity coordinates manufactured using two types of printing tools

The main parameters controlled during the welding process are: ultrasound power, welding time, tool pressure and warm stage temperature. The sought accuracy is usually ± (2.5 ÷ 3) μ. To ensure the required accuracy before the welding process begins, an automatic workpiece scan should determine where the welded junctions will be formed. Another option is using a linear position detector, which measures wire strain with a high resolution, but this

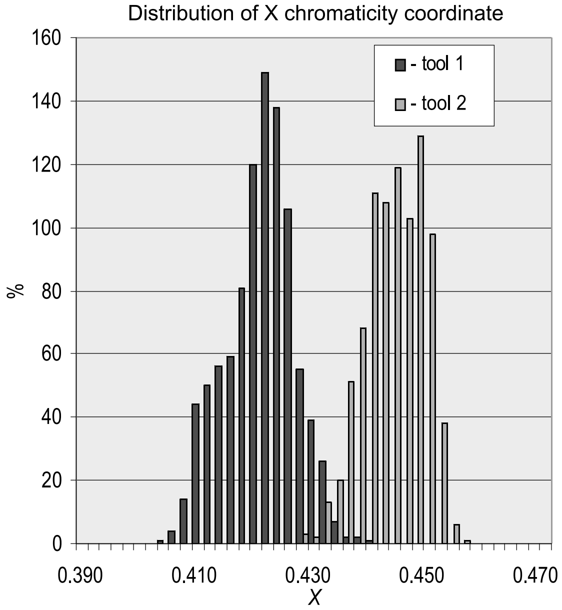


Fig. 14. Distribution of *x* chromaticity coordinate for LEDs manufactured using two types of printing tools

demands for a significant prior work determining the technological corridor parameters.

After microwelding, appearance control must be carried out to establish whether the device corresponds to international standards. This is done by means of an optical microscope or optical inspection devices.

In addition, **the welded junctions** are tested.

Usually for this aspect, equipment is needed, which provides junction testing for tension and shear by a force of up to 5 kg. The parameters of the tool are selected based on junction strength. For example, a wire junction of 17 ÷ 32 μ requires cartridges with the force of no more than 250 g for a shear test. The sample under test is installed on a motorized platform and fixed. Then a semi-automatic mode tool comes down onto the surface under test. A sufficient interval of the stage moving along *X*-*Y* axes amounts to 50 mm with positioning accuracy equal to ±10 μ at 50 mm movement, with axes *X* and *Y* resolution equal to ± 1 μ and with axis *Z* resolution equal to ± 0.125 μ. The system automatically tests samples, smoothly loading the wire junction and measuring

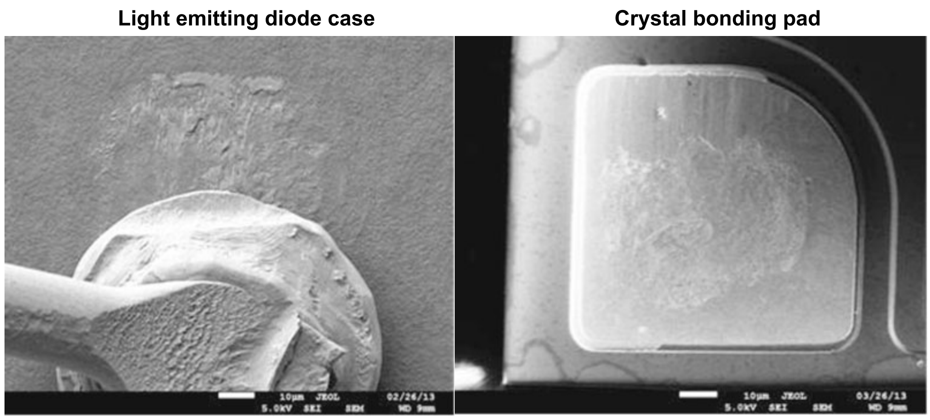


Fig. 15. A poor-quality welded junction

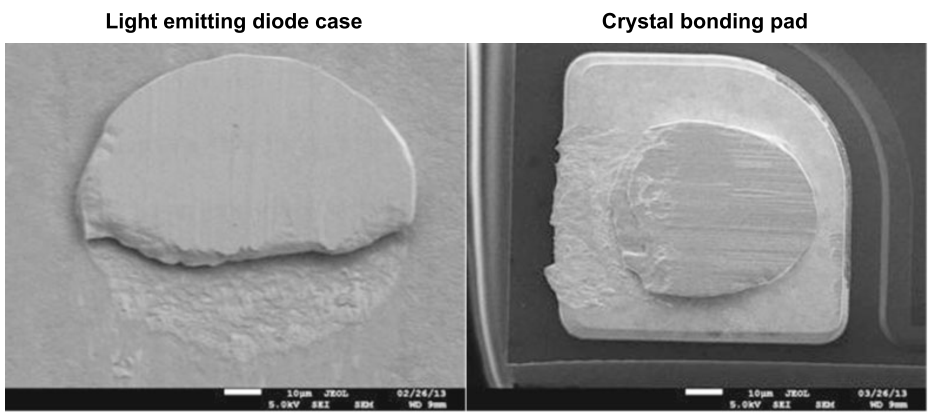


Fig. 16. A high-quality welded junction

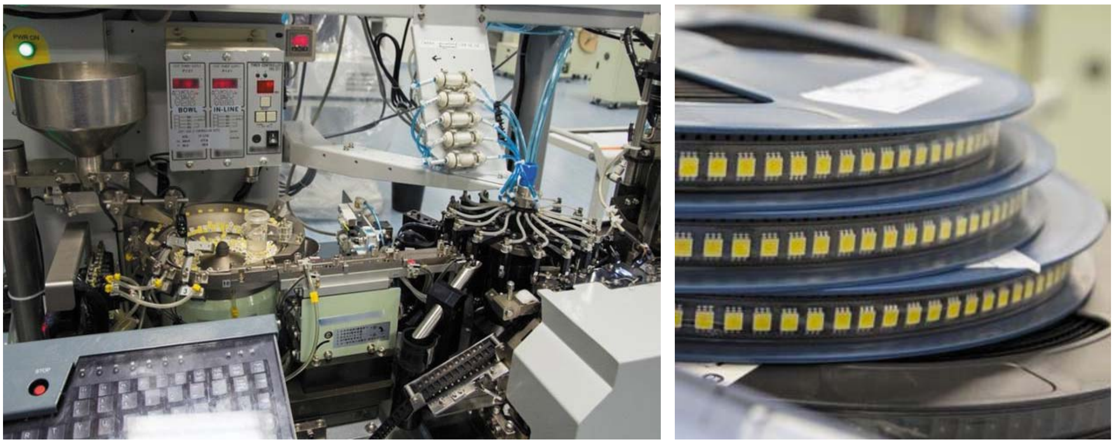


Fig. 17. Automated unit for packing LEDs

the load, with which its destruction occurs. When verifying serial processes, carrying out non-destructive testing is enough that is when the system only loads a junction up to a preset force. The equipment software should allow analysis of critical load values for a clear statistical image to be constructed, based on which the process engineer verifies the process or performs some corrections on the production mode (Fig. 8).

In LED mass production, it is very important to provide reproducibility of chromaticity coordinates, as this is one of the main consumer characteristics. This parameter is influenced by many factors. In Fig. 9, these factors are separated by a functional principle.

A considerably bigger repeatability of chromaticity coordinates is observed for structures with a large number of crystals, which is caused by averaging non-uniformity distribution of phosphor particles in the mixture. The *face-up* crystal structure ensuring light output through a side surface, also improves colour averaging due to additional light reflections inside the LED case (Fig. 10).

For a preset LED structure, chromaticity coordinates can be influenced by such factors as standard deviation of the inner case size, fluctuations in the reflection factor of the case surface, standard deviation of crystal characteristics within power and wavelength groups.

Change with time of the silicone compound viscosity can be a serious problem. This can lead to the dosage errors and as a consequence, can essentially affect colour characteristics of the product. The problem can be solved using dosage by means of the volume measurement (*volumetric*) principle instead of dosage by means of the *time-pressure* method.

When depositing a mixture of the phosphor with silicone compound using the hole dosage method, a problem arises connected with sedimentation of phosphor particles during the deposition itself, and during the mixture hardening.

In some cases, application of tiksotropny additives is a sufficient technological solution (Fig. 11).

Selection of the drying temperature profile plays an important part. The main factor is the change degree of silicone viscosity at the drying initial stage.

The process should be adjusted either for full phosphor sedimentation, or for total sedimentation absence. Work in a partial sedimentation mode leads to emergence of non-uniform displacements of chromaticity coordinates.

An important condition is the development of methods for technological silicon tests and determination of their result evaluation criteria concerning chromaticity coordinate repeatability (Fig. 12).

Reproducibility of the LED radiation colour can also depend on the process stability at previous stages of assembly.

For example, reducing the size of the crystal joining material can have a strong influence (Figs. 13, 14).

Optimisation of the crystal mounting process parameters and of the hardening temperature profile, a high-quality preparation of the case surface, constant process monitoring, use of optically transparent joining materials or use of these materials with reflection factor close to the LED case material reflection factor, can reduce this influence to a minimum. When switching to use of silicone basis joining materials, the partial power loss of the ultrasonic oscillations transformed during the microwelding operation should be considered. This loss is connected with the mentioned material property change regarding hardness, in comparison with the materials on epoxy and hybrid basis.

Standard junction tests for mechanical strength should be added with an analysis of the samples under test using a scanning electronic microscope (Fig. 15, 16).

After formation and drying the phosphor layer and the lens, group workpieces are subjected to **the separation process.** For the separation, precise dies are used. The automation degree depends on the output volume and on LED overall dimensions.

At the finishing **packing** operation of the LEDs intended for surface installation, it is efficient to use automatic equipment (Fig. 17). Before packing, the LEDs should pass additional working capacity and polarity check control. Stability of the process is ensured by an optimum tool selection and vacuum level on the placement head, as well as by temperature of the press for sealing the cover ribbon.

In this article, we have only described main principles of running a mass production LED manufacturing process. Certainly, a process engineer intending to develop such a process and to start production on it, faces many more challenges and problems. Here, within only one article, we provide a general idea about equipment selection, the most important controllable parameters and the key problems for all basic LED assemblage operations. We hope that our experience will be useful both for newcomer engineers, and for experienced specialists. This work was supported by the Ministry of Education and Science of the Russian Federation within the 02.G25.31.0014 contract of 2/12/2013.

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THE DEVELOPMENT STRATEGIES AND TACTICS OF THE RUSSIAN LIGHTING INDUSTRY: ADDRESSING THE TARGET OF DECREASING ILLUMINATION POWER CONSUMPTION BY HALF WHILST IMPROVING LIVING CONDITIONS

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ABSTRACT

The article gives a short historical outline of the development of the lighting industry in Russia; the shortcomings of the existing situation are analysed, and protection measures for manufacturers and consumers of domestic lighting are considered. The article presents proposals on for increasing energy efficiency of illumination devices and stimulating of energy-effective lighting product manufacture.

Keywords: energy efficiency, electric illumination, new light sources, light emitting diodes

1. A short historical review, production state, product import and export

Twenty years ago, by the time of the USSR's disintegration, the country's lighting industry represented a high power state production machine under the auspices of the Ministry of Electrical Engineering Industries. In practice this involved 150,000 workers manufacturing more than one billion incandescent lamps and 155 million fluorescent lamps, 82 million luminaires, including 25 million luminaires with discharge lamps of low and high pressure (mainly MAL). The country was almost entirely self-sufficient in the production of lighting products, except for sodium, metal halogen and compact fluorescent lamps.

This branch of state industry included 24 lamp factories, 36 factories of lighting fixtures, eight enterprises producing ballast and control equipment for discharge lamps. Alongside these, there existed, more than 200 relatively small enterprises, which produced household luminaires, and were not a part of the state industry branch.

Among the listed production enterprises, the following are noteworthy:

– "Lisma" (Mordovia, eight factories, 33 thousand workers);

– "Luis" (Armenia, nine factories, 11 thousand workers);

– "Vatra" (Ukraine, five factories, nine thousand workers).

Together with these giants, one should note such associations and large-scale factories as Azerelectrosvet, Rizhskoe association, Iskra association, Poltavsky, Mali-Saisky, Brestsky, MELZ and others.

Despite lagging behind the best international companies by their technological level and quality of products, the state industry met the needs of the national economy almost completely, though to a large extent using outdated technology.

It is also important to note that by this time three research and development scientific institutes had been established and were working successfully: VNISI (Moscow), VNIIIS (Saransk) and VPKTISvet (Ternopol).

In the years following the collapse of the Soviet Union, this single state industrial branch ceased to exist; connections between enterprises, which were now in different states, were destroyed. There was no uniform scientific and technical policy, centralised financing or control. The manufacturing enterprises quickly lost their position, lighting products became deficient and the market gap was quickly filled with imported products. In the context of a total absence of domestic production of many modern lamps (compact fluorescent, third generation thin fluorescent lamps of T5 type, metal halogen lamps, and later light emitting diodes and electronic ballasts), imports grew at a quick rate. Unfortunately, as a rule, the imported products were of a poor quality [1].

Looking at import lamp products as a whole, in 2011–2012 these accounted for more than 60% of the market. Considering groups of lamps separately, the data, sadly, are as follows: CFL – 100%, lamps of T5 type – 100%, MHL – 90% (2010), HPSL – 93% (2010), MAL – 57% (2010), fluorescent tubular – 38%, incandescent lamps – 33%. The import volume of outdated electromagnetic ballasts, outlawed throughout Europe, increased 2.3 times during the last five years due to demand of these products in our country; their manufacturing production is up and running in Germany, Austria, Italy and Spain [1, 2].

2. The key shortcomings of the lighting industry and national damage sustained due to an underdeveloped light engineering field

Fourteen% of electric energy generated in Russia is consumed by illumination, this is about 137 billion kW hours of electric energy a year. Russian industrial, residential and public buildings represent the greatest power saving potential. Russia's total potential power savings are huge: 56 TW hours a year. This is equivalent to reducing emissions by approximately 39 million tonnes of $C0_2$ a year, and the proposals described in this paper are aimed at achieving 50–60% of this potential.

As noted above, the annual consumption of electric power for illumination in 2007 amounted to 137.5 TW hours, which corresponds to 14% of the total electric power consumed in the country. Illumination is the cause of 97 Mt of CO_2 emissions annually. More than 50% of the electric power consumed by artificial illumination systems is accounted for in households and industrial buildings.

According to expert evaluations, in 2020 the total quantity of electric power consumed in Russia for illumination will amount to approximately 157.8 TW hours, which corresponds to a modest gain of less than 2% a year. However, this scenario does not take into consideration that real illuminance levels are still very low in many cases (sometimes twice as low as recommended by international standards for industrial enterprises, schools, hospitals etc.), and that over the coming years the elderly population will increase (older people require higher levels of illuminance).

These reasons inevitably lead us to the conclusion that if no actions are taken the power demand for illumination will grow going forward.

It should be noted that:

– 35% of luminous flux is generated using ineffective incandescent lamps in Russia, whereas in the western countries this does not exceed 20%;

– The rate of residential market penetration for energy efficient light sources (CFL) is very low in Russia compared to any western countries (over the last three years it has only increased ten times);

– Uptake rates for T5 lamps in public, educational and office buildings are almost imperceptible (finding T5 lamps on the Russian market is a problem). T8 lamps used in Russia (and even older *T12* lamps) are products first or second generation products, whereas only third and fourth generation lamps are used in all new installations in western countries;

– Installed power capacity in lighting devices (LD) of working areas of public buildings in Russia is close to seven W/m^2 per 100 lx, whereas in the USA and Europe this value is about 2.5 W/m^2 per 100 lx;

– In Russia, for generation of 1 Mlm·h luminous flux, 36 kW·h are required, whereas in western countries no more than 25–26 kW·h are required (according to 2009 data) [3];

– Automatic illumination control systems, which are widely in use in the west, are almost non-existent on the Russian market.

As a result, annual light consumption in residential buildings in Russia is almost ten times less than in the USA [4]. Hence, the population of the Russian Federation obtains significantly less vital light energy. Power consumption in Russia for 2009 is presented in Table 1.

In 2010 the total volume of the lighting market, including import goods, amounted to approximately $2.5 billion a year and most likely will continue to grow.

3. Key disadvantages of lighting products, with a focus on ballasts [4]

1. As V.V. Barmin noted [5], most often ballast failures occur because of winding burn-out in an emergency mode. As a rule, devices fail during 5–25 minutes from the beginning of the test.

Table 1. Power consumption in Russia

Group of illumination equipment	Installed power capacity, GW	Consumed electric power, GW·h per year
Industrial and commercial buildings	28	85000
Public, educational and office buildings	8	12000
Street illumination	1.5	4500
Residential sector (private sector)	15	20000
Agricultural sector, including the population	5	16000
In total	57.5	137500

2. The actual lamp power provided by all devices checked at Ardatov, is overstated. For lamps of 36 W power claimed, the measured power value is 23–26 W, which is a direct deception of the end user. This is possible due to the buyer's incompetence and because end user control is not possible.

3. The power factor of a LAMP-PRA package is lower than maximum permissible values at 64–75 % for a number of import ballasts, which is inadmissible for economic reasons.

4. Winding temperature excess in operating conditions is 20–30 °C compared to the one specified on the ballast (t_W value), which is reflects negatively on device service life.

5. The working current of the lamps is underestimated, it is lower than the value permissible by the applicable standards. Starting current is underestimated or is at a lower limit, and that does not provide reliable and quality ignition of lamps throughout normal service life.

6. Practically all tested ballasts have increased power losses, and by energy efficiency, a significant number can be classified as having inadmissibly high losses.

7. As a rule, parameters declared on ballast labels, do not correspond to the values measured.

8. A very confused designation system is used for marking of many samples, so it is often impossible to identify the actual manufacturer, true parameters, as well as where they were tested, by whom, and whether they were tested at all.

There are also many other disadvantages.

Monitoring purchases and tests of luminaire samples also confirm multiple infringements compared to reference documents, which lead to abrupt decreases of technical and efficiency indicators of the light sources, which can be dangerous to the life and health of the consumers. Some of the most frequent breaches are listed below.

1. Uncertified, low quality component parts are used for luminaire assembly, including: ballasts, lamp holders, terminal blocks, starter holders, pulse starting devices, etc.

2. Components are used, which are not appropriate for the real conditions in which they work.

3. To manufacture cases of diffusers and other heat-stressed elements of luminaires, materials are used with inadmissibly low heat-resistance, which reduces their service life drastically and makes them unsafe under operating conditions.

4. To manufacture diffusers and other lighting elements of luminaires, light-fugitive plastics are widely used, for example polystyrene, styrene and acronitril, as well as polypropylene, which are not of lighting grade, but of general purpose industrial grade. This leads to rapid decrease in the lighting parameters of luminaires, yellowing, destruction of materials and deterioration of the device appearance.

5. Lighting fixtures do not provide an optimum temperature mode for fluorescent lamps. Many structures have median temperatures surrounding the lamp in excess of 65–70 °C, and this leads to an unacceptable decrease of lamp luminous flux.

6. Domestic and international standards and rules are regularly violated, specifically those relating to units of grounding, luminaire wire lead-ins, power factor, and other basic requirements for luminaire structures.

All of the reasons listed lead to poor quality LDs, with low reliability and increased operational costs.

4. Regarding protection of domestic manufacturers and buyers

European Union countries have brought in a high customs tariff, amounting to 66 %, to protect against cheaply imported lamps of Chinese production, which do not guarantee their declared energy efficiency. A clear example of direct prohibitive measures against the use of obsolete technologies is the US Energy Policy Act signed by president Bush on the 8th August 2005. The law effectively prohibits the manufacture and use of electromagnetic ballasts for most mass application fluorescent lamps in the US from 2009. Contrastingly, we in Russia, counter to global trends, continue to develop the domestic production industry of these ballasts, instead of financing the development of more promising directions. Another well-known example is the implementation by EU member states of directive 2000/55/EC, developed in association with the representative body luminaire and component manufacturers. The directive prescribes a gradual elimination from the market of electromagnetic ballasts with high electric power losses, and of luminaires with such ballasts. The implementing measure does not only protect manufacturers of superior products, but also the end consumer from operating inefficient and outdated devices. It also realises crucial government energy saving programmes and contributes to meeting international agreements on cutting emissions of the substances, which have a negative impact on the Earth's atmosphere and climate.

It is typical that no countries have ruled against the manufacture of inefficient outdated products under the condition that the products are distributed outside of their borders, for example, to our country.

Here, however, it is well known that the Russian authorities have completely distanced themselves from regulating the domestic market for lighting. The market is self-regulating, with unchecked powers over technical policy, energy efficiency, and almost all kinds of safety parameters. This has led to an uncontrolled situation of a permissiveness and absence of responsibility for manufacture, purchase and development of poor-quality products.

The lack of much needed government control and the low level of NGO influence, has created a Russian lighting market with inefficient and obsolete products, which are often unsafe and typically phased out from use in their countries of origin.

In order to protect domestic consumers from inefficient, poor-quality products, and in order to stimulate domestic manufacturers towards producing more products, which meet the needs and requirements of society and represent the latest technological development trends, V.V. Barmin proposes a series of measures, including, but far from limited to, the following.

1. To develop a national programme "Green Light Russia" following the example of the *Green Light* initiative, which has been successfully implemented in many countries. The programme will bring together and coordinate the activity of government bodies, NGOs, manufacturers and consumers of lighting products. The programme would focus on reducing energy consumption and safeguarding the environment. Crucially, a key implementation mechanism for the programme must be a state endorsed system of measures, which is designed to support the application of energy saving lighting products. We believe that development of such a programme would be in keeping with the spirit of the age. As national programmes concerning public health and education are being realised, the Green Light Russia programme could become a complementary measure to promote improved ambient conditions in educational and public health buildings, directly influencing the health and wellbeing of students, as well as the wider population.

2. To develop mandatory standards of minimum efficiency for the majority of mass market lighting products. (The specific standardisation parameter will depend on the product type.)

3. To develop an evaluation protocol of ballast efficiency for fluorescent, based on lessons learnt in Western Europe, including, for example, recommendations made by CELMA to EU member states.

4. Before a national protocol of ballast efficiency for fluorescent lamps is developed, the production and import of those ballasts, which are classified as high power loss devices by Western standards, should be prohibited by state legislation. These are devices, which have essentially no limits for power loss. Today, due to our lax market systems, a large number of such devices are imported into Russia.

5. When certifying products, certification bodies should be very strict about IDENTIFICATION and labelling of certified products. It is unacceptable that a luminaire with stated lamp power of 36/40 W only provides lamp power of 22–23 W. What exactly are we certifying?! It may make sense to label products with two distinct pieces of standard performance information; one referring to safety limits, and one regulating key product parameters.

6. There is a necessity to finally provide an objective assessment on the practice of import and application of devices, which do not correspond to the

nominal normalised voltage of 220 V in Russian power supply circuits (as opposed to 230 V).

7. The present situation of Russian lighting necessitates the implementation of a mechanism which, as part of a suite of measures protecting domestic manufacturers, would prevent massive injections of poor-quality and obsolete products onto the domestic market.

8. Certainly, as a temporary measure, objectively set duties and quotas could be applied to imported lighting products. However, establishing quotas and duties, including those which prohibit obsolete products, must not negatively affect the end consumer. Examples of these low level products include electromagnetic devices equivalent in power loss to classification grades *D* and *C*, as well as luminaires, which contain such low grade components, devices for HP discharge lamps (MHL and HPSL) without thermal protection, etc.

9. It would be useful to develop a system of accountability for deliberate publication of false information in manufacturer catalogues and reference documents, which misleads consumers.

10. One should consider the possibility of communicating the recommendations (al least) of all relevant associations through the Light & Engineering (Svetotekhnika) journal. Incidentally, this would enable the growth of authority and influence of these associations in the lighting sector.

It is necessary to develop evaluation criteria for the technological level of products:

– The performance of products at appropriate technological levels should be confirmed through positive laboratory testing results across the full range of applicable international standard parameters for a specific product type, not just limited to safety requirements.

– The products should not only meet safety standards but also all requirements of standard documents, which determine their key technical parameters.

5. How to raise illumination efficiency

In the context of a noticeable energy deficit in a large number of Russian cities, the words of science fiction author Arthur Clarke seem very relevant: “the kilowatt hour will be the universal unit of exchange”. One seventh of all power generated in Russia power is consumed for illumination. Therefore, electrical energy savings is the central focus of attention in the lighting industry. In the following section, we will compare various light sources in order to understand how energy consumption can be reduced without reducing illumination potential.

Electricity demands are growing continuously in Russia. There are two possible directions: increasing generating capacity or decreasing electric energy consumption without compromising on illumination quality. As with many similar dilemmas, the correct answer is somewhere in the middle. It should be noted that cost of creating energy generation capacity at different types of power stations is approximately $1,000 – $3,000 per kilowatt. However, decreasing installed power per one kilowatt of illumination is $150–200. This is a huge difference, not only in the price but also in environmental impact.

Around the world, and specifically in the countries involved in the International Energy Agency (IEA), the main illumination energy saving measures include the following:

– Use of compact fluorescent lamps (CFL) instead of incandescent lamps (IL);

– Installation of electronic ballasts;

– Application of fluorescent direct lamps of *T5* type;

– The growing and future use of light emitting diodes.

Which methods can decrease energy consumption?

There are only two such methods: to reduce the power capacity of illumination devices (without compromising on illumination conditions) and to reduce the usage time of electric illumination.

The operating time of illumination can be automatically controlled, with lights turning off in the absence of people, at night, or at sufficient natural illuminance. Lamp luminance can also reduced, for example, at night in streets or the standby illumination in industrial premises.

The luminous efficacy of lamps and luminaires, it is determined by that electric power consumed, which is converted to light and characterised by the luminous efficacy parameter, lm/W.

The most mass market, simple and cheap incandescent lamps, which are widespreaded in everyday life, have two significant disadvantages in terms of energy saving. Firstly, these lamps have a low luminous efficacy; only 6–8 % of power consumed by the lamp is turned into light energy. Secondly, they have an unacceptably short service life; irrespective of countries of origin and manufacturers, this is about 1000 hours. Working for five hours a day, these lamps fail after seven months. During

Table 2. Comparison of data for ILs and CFLs

	Incandescent lamps	Compact fluorescent lamps
Luminous efficacy, lm/W	10–13, seldom 15	60–80
Average service life, h	1000, irrespective of manufacturer	Noo less than 8000, 12000–15000 for lamps of some manufacturers
Service life in household use, month	6–10	60–120
Price of a lamp, rbl.	15 for a lamp of 60 –75 W power	3–35* for a lamp of 11–13 W power
Cost of a lamp package for 10 years, rbl.	300	200–400
Cost of the consumed electric power, rbl. at the tariff 3.45 rbl. for one kW·h for a ten year period	5037	1007
Saving of the cost for electric power, rbl.	–	4030
Payback period, years	–	0.6

* In 2007 a fluorescent lamp of 20 W power costs 200 rbl.

the dark winter season, residential lamps in Moscow operate for ten or more hours a day.

Russia consumes over 14 % of all generated electric power on illumination, i.e. more than 137 billion kW hours a year, 30 % of which is consumed for household use. Although the portion of generated electricity consumed for illumination in the USA is even higher, at over 20 %, the energy needed to generate one illuminance unit (1 lx) is 1.3–1.5 times less than in Russia. This can be explained by the dominant application of energy efficient lamps in household use. It follows that the Russian population receives substantially less light than people in the USA.

Although incandescent lamps have played a huge role in mankind's development, today they are completely outdated light sources. In a large number of countries this fact is clearly understood and strong phase out measures for incandescent lamps are being implemented. For example, in the USA a presidential ruling was issued that beginning from 2011 incandescent lamps of 100 W power are to be taken out of production and application, in 2012 – lamps of 75 W power were to be phased out, and so on until 2014, when incandescent lamps should be completely eliminated. The Australian government decreed a complete switch over to compact fluorescent lamps by 2012. The New Light project, instigated by former Russian president D.A. Medvedev also provides for a gradual phase out of incandescent lamps from production and application, and for their replacement with energy-efficient lamps, CFLs in the first instance. At the same time, the New Light project does not envisage any measures to aid the development of domestic manufacture of energy-efficient lamps. This renders the phase out project unrealistic, or makes the country completely dependent on imports [1].

Table 2 compares the characteristics of incandescent lamps (IL) and compact fluorescent lamps (CFL).

Table 3 presents some characteristics of the main groups of light sources, of which the main one is light energy generated over the service life. If we take the light energy level of an incandescent lamp as a unit, then we can see that all other types of lamp generate much more light energy.

When only using one line of fluorescent lamps, considerable power savings are possible. This is confirmed by the example calculation of energy saving potential for Germany (drawing), where normal lamps T12 of 38 mm diameter are taken as the base case (0 %). Application of lamps T8 (tube diameter is 26 mm) demonstrates saving 7–10 % of electrical energy. Thin lamps T5 (tube diameter is 16 mm) can give energy saving of up to 42 % in comparison with the T12 lamps base case. Introducing state-of-the-art devices for lamp luminous flux control and using sensors for natural illuminance, can reduce the volume of energy consumed by 71 %. A full suite of energy saving measures, including motion sensors, can yield energy savings of 82 % against the initial T12

Table 3. Main characteristics of light sources (of one lamp 2010)

Light source type	Average service life, thousand h	Luminous efficacy, lm/W	Specific energy generated over service life (average value)	
			Mlm·hr/W	Rel. unit.
Incandescent lamps	1	8–17	0.013	1
Fluorescent lamps	10–20	48–104	1.140	88
Compact fluorescent lamps	5–15	65–87	0.780	60
Mercury arc lamps	12–24	19–63	0.738	57
High pressure sodium lamps (HPSL)	10–28	66–150	2.050	157
Metal halogen lamps	3. 5–20	68–105	1.020	78
Light emitting diodes	25	80–90	2.125	163

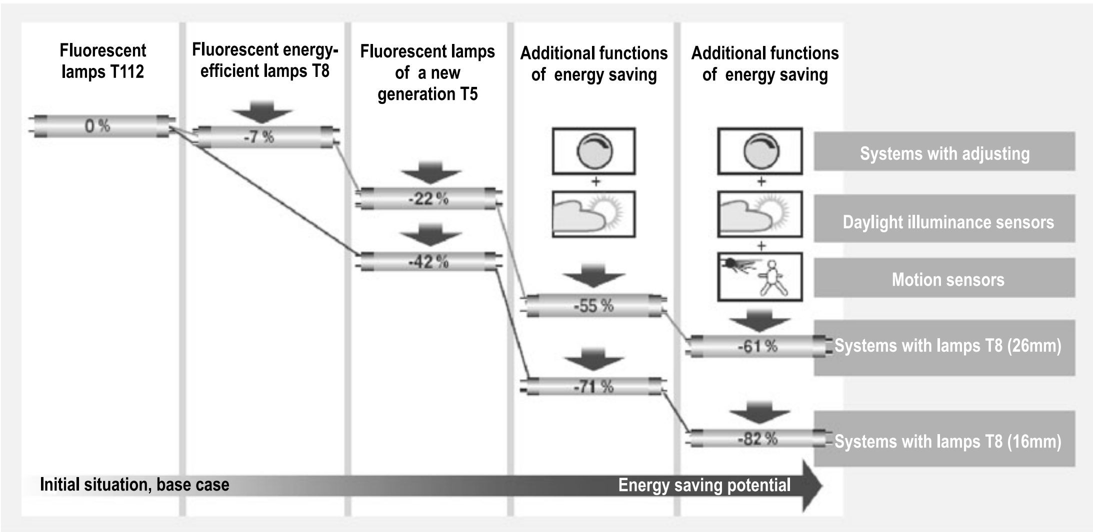

Fig. Energy saving potential (per year) in Germany when using various illumination facilities

lamp base case. It is worth remembering that one line of lamps is considered for these calculations.

Of greatest interest and development potential is the light emitting diodes (LED) technology direction, where many companies are already focusing their energies.

The average luminous efficacy of commercial light emitting diodes by the top manufacturers is between 70 and 90 lm/W. Cree Lighting Company had pledged to reach efficacy of 150 lm/W during 2009–2010, and this was achieved, although only for laboratory prototypes, which is nevertheless a great achievement. There are already many buildings and spaces today where light emitting diodes are applied even for general illumination, although this is very expensive. For example, in the Turning Torso skyscraper in Malmo (Sweden), a 190-meter twisting tower, even the corridors are illuminated using light emitting diodes (along the cornices).

However, it is unlikely that we can expect a significant contribution to energy saving from light emitting diodes within the next 3–5 years, as using them for general illumination is too expensive at present, and production volumes of luminaires with LEDs is still very low.

The properties of light emitting diodes, which in the near future will make them the most economical light sources, are listed below:

– A high luminous efficacy (working up to 100–150 lm/W in the long term);

– A low power consumption;

– A high efficiency of light devices and luminous flux usage in illumination devices;

– Small dimensions (point or plain devices);

– Durability (more than ten years of continuous operation);

– Absence of luminous flux ripples (in high-quality operation systems);

– Radiation ability at various spectrum intervals;

– An opportunity to decrease the assurance factor of illumination devices in the future due to their stability and long service life;

– An opportunity to use LEDs for illumination of objects where colour can fade (works of arts, printed products, textiles);

– A high stability against external influences (temperature, vibration, impacts, humidity);

– Electrical and explosion safety;

– An opportunity to develop unmanned (no maintenance) luminaires;

– A high degree of controllability (the possibility to construct systems of multilevel illumination control);

– A high adaptability in mass manufacture.

VNISI Open Company has calculated electric power saving potential for illumination devices. **Electric power saving can be achieved through improvements of illumination facilities and illumination methods, the savings can amount to 45–50 %.**

The most appropriate spaces for a gradual transition to light devices with light emitting diodes are rooms and open spaces with a low level of normal required illuminance, where illumination is needed most of the time (more than 4–5 thousand h/year) and where people are not constantly present. With ever increasing energy costs and with improving parameters of light emitting diodes, their fields of effective application will grow. A separate sphere for light emitting diode application is architectural illumination.

6. The task of stimulating production and application of energy-efficient lighting products

In order to convert the lighting market so as to stimulate production and consumption of the most energy-efficient products using market drivers instead of regulatory ones, we need to enact a suite of coordinated activities, with full support from the state. Some of these measures are listed below.

1. *Standards of energy-efficient illumination; legal rights and institutional basis*

1.1. It is necessary to review the Building regulations, Sanitary regulations and other standards with a view to the following amendments:

a. Introduction of a maximum permitted total power of illumination devices for individual rooms and whole buildings, depending on building type and function, as well as for external illumination devices.

b. Introduction of limits on the use of luminaires and lamps with a low luminous efficacy, depending on the normal illumination level and quality required, and on annual operating time of illumination devices. As a rule, lamps performing below the following thresholds should not be used: luminous efficacy less than 50 lm/W, colour rendering index less than 80, service life less than four thousand hours, cos $\varphi > 0.9$, pay-back period < 2.5 years.

c. Limitations on the use of lamps with a big drop in luminous flux; this will make it possible to sharply reduce the normalised assurance factor for decreasing installed power capacity of illumination devices.

d. Prohibition of luminaires with discharge lamps and electromagnetic ballasts with high power losses; conversion of luminaire production to electronic ballasts with losses less than 10 %.

e. Introduction of firm specifications for operational maintenance of illumination devices (cleaning of luminaires and replacement of lamps) to ensure further possibilities of to decreasing the assurance factor and improving illumination quality.

e. Introduction of firm specifications of lighting product quality, to reflect not only safety parameters, as in IEC documents, but also to account for luminous efficacy of the luminaires, cos φ, power consumption and degradation of characteristics while in service.

f. Introduction of a requirement to equip all large-scale illumination devices with automatic switch-off and switch-on systems, based on sensors of natural illumination, people presence’s and/or traffic intensity.

1.2. Regular monitoring of market development. His should include updates on how the market is responding to and meeting new measures and standards. Monitoring should also include an evaluation of lighting product quality control levels at a limited number of highly-specialised certified centers, which have the necessary expertise and equipment for quality control. Strictly monitoring quality control procedures followed by CFL manufacturers, introducing a system of penalties for poor quality products.

1.3. Strict customs controls for imported products for valid certificates obtained exclusively from specialised and licensed certification centers. Certified luminaires should also be checked for their component make up (sockets, terminal blocks, etc.) which should be certified by the same laboratories.

1.4. Establishment of independent expert panels of leading specialists for controlling energy efficiency and ecological impacts of illumination installations for the biggest and most widespread buildings and construction projects.

1.5. Introduction of an "energy-effective product" label to be placed on products which meet the new criteria.

2. *Support of the component supply chain for energy-efficient illumination devices*

2.1. Establishing systematic international networks with leading centres of energy efficiency in countries, which have made the greatest strides in this direction: Germany, Great Britain, China; mobilising these networks in order to identify standard specifications for energy savings and to exert influence on companies manufacturing poor-quality products in these countries.

2.2. Providing scientific and technical guidance to foreign suppliers of imported products or their components in order to improve the product quality.

2.3. Assigning the Moscow Light House the responsibilities of a knowledge centre for energy efficiency in lighting, a centre for information provision and promotion of energy saving illumination devices.

3. *Effective illumination in residential and public buildings of Moscow*

3.1. Regular planned monitoring activities of municipal buildings, schools, higher education institutions and hospitals in order to uncover incidents of inefficient illumination and develop plans for their replacement (using recognized energy audit methodologies).

3.2. Developing a system of bank loans for replacement and upgrade of illumination installations; credit facilities can be based on savings funds from energy cost reduction.

3.3. Repaying some of the saved funds (no less than 50 %) to the staff enabling energy savings through illumination device replacement. Payouts should continue for a period of three years after the initial upgrade loan has been repaid.

3.4. Installing pilot illumination installations in schools, hospitals and higher education institutions. These pilot installations will act as demonstration sites, which will host consultation meetings of building staff and project managers and architects of reconstruction projects.

3.5. Development and publication of mass market books about pilot projects of energy-efficient illumination and the results obtained.

3.6. Developing a forecast to 2020 of illumination development in public and residential buildings in Russia, accounting advanced scientific and technical progress.

4. *General measures for stimulating energy saving in illumination devices*

4.1. The state should enact a law, according to which:

– All government agencies convert to CFLs and T5 FLs with electron ballasts and LEDs within three years using budget funds;

– All manufacturers of CFLs and their ballasts, as well as LEDs, are exempt from VAT;

– Tender processes for lighting product delivery for public sector organisations give prevalence to companies which meet conditions under paragraph 1.1 above, and also guarantee a price of no more than 75 rbl. for a CFL with luminous efficacy of 50 lm/W, 100 rbl. – for a CFL with 60 lm/W, 125 rbl. – for a CFL with 70 lm/W, ensuring a payback period ≤ 2.5 years.

4.1.2. Power supply companies lower electric power tariffs for consumers, who achieve energy savings of 30 % or more as a result of switching to CFLs, T5 FLs, electron ballasts and LEDs which payback within a period ≤ 2,5 years.

4.1.3. Beneficiaries of the support fund for the poor and pensioners over 65 years old shall receive, at the expense of the fund, three CFLs free of charge annually.

4.1.4. Bank loans at lowered interest rates and increased repayment periods shall be provided under state guarantees.

4.1.5. Funds, including those already allocated by the budget to introduction of new generating capacity, are directed at stimulating CFL and LED manufacturers, with the aim of decreasing the sale price of efficient light sources and improving production methods.

4.2. Establishment of "noncommercial partnerships": design, sale, assembly and power service companies and their relative bank structures. These partnerships can ensure comprehensive and high quality production of energy efficient illumination devices, which are demanded by the customers (proposed by A.V. Savelyev's, "Kosmos-Energoservice").

4.3. Stimulating the emergence of small-medium enterprises which will aim to increase energy efficiency of illumination devices for public sector buildings and the residential sector.

4.4. Developing a mechanism of economic incentives for energy efficiency improvements in the public sector.

4.5. Developing systems of leasing for CFLs, T5 lamps and LEDs.

4.6. Supermarket chains mobile an incentivised take-back system for failed CFLs, which provides a 20 % discount on new lamps purchased simultaneously.

4.7. A wide open discussion of measures for increased of energy efficiency of illumination devices shall take place in the Light & Engineering (Svetotekhnika) journal.

One of the major strategic questions, on which the choice of change direction depends, is identifying partners for co-production. The external partner should be interested in penetrating the untapped and boundless Russian market. The Russian partners, who would provide infrastructure, workers and market connections, should obtain the newest designs, technologies and in some cases, modernised equipment. Some examples of such conglomerates are Philips-Optogan, VNISI-Schröder and Northcliffe with daughter companies in Kiev, Prague, Kaunas, Torn-Vladasvet. It is important that the foreign partner is highly advanced technologically and a market leader in product quality.

With technical and quality control for mass-market imported products essentially non-existent, the Russian market has been flooded with lighting products of questionable quality. Serious violations of standard requirements allow suppliers of such products to drastically cut prices and thus become competitive on the Russian market. Sub-standard goods have become a means of successful business. This situation is unacceptable from the consumers' point of view. It is also has negative impacts on bona fide domestic manufacturers of lighting products, violates the basic principles of the civilized market, in particular the principle of fair competition.

7. Safeguarding the young generation from possible harmful effects of low-quality illumination devices

In Russia, and Moscow in particular, the state of sight amongst children and young people is a cause for concern. Many young people (22–25 %) graduate from school with sight deficiencies, and the pathology increases during education by 2.4–2.5 times. One of principal causes of this negative and dangerous process is the unsatisfactory state of school illumination.

A mass investigation of state of illumination in 193 schools in 21 cities and in 15 villages, organised by the Svetotekhnika journal in 1980–1981, showed that the standards in 70 % of cases were not met even by half. Unfortunately, the recommendations on the improvement of artificial illumination, made as a result of the study and sent to the Ministry of Public Education, largely have not been implemented.

Follow-up investigations in 2003–2004 of schools in Moscow (10 schools), Saransk (35 schools) and Tomsk (10 schools) showed further deterioration of the illumination conditions. The study found that 80–90 % of classrooms rooms did not meet the standard requirements for workplace illuminance, and 100 % of classrooms did not meet requirements for blackboard illuminance. In the Moscow schools surveyed, illuminance on the boards amounted to 130–140 lx at the rate of 500 lx, and illuminance in the rooms amounted to 50–100 and 250–260 lx at the rate of 400 lx. Most of the schools illuminated with fluorescent lamps, had a luminous flux ripple level which exceeds the maximum permitted level by 2.5–3 times.

According to the relevant health and safety standards, these illumination conditions are classified as harmful and hazardous for health, contributing to development of diseases.

It should be noted that Russian domestic standards for many types of classrooms (computer rooms, workshops, art studios and gyms) are significantly lower than European standards implemented for about ten years.

None of the schools surveyed applied preventative ultra-violet radiation lamps, which is an important modern day sanitation method for premises inhabited by children and teenagers.

Despite the fact that "Changes #1 to the Building Regulations 23–05–95*" brought in in 2003, prohibit the use of incandescent lamps for illumination of classrooms, these lamps are still used in many schools within long obsolete inefficient luminaires. The resulting overspend on electricity in these schools amounts to 35–40 %.

At the schools surveyed, a considerable part of the luminaires has been operating for more than 20 years. In Moscow, 30 % of classroom luminaires are in non-working order. The noise levels created by the ballasts of many old luminaires exceed acceptable levels and distract from study.

This situation is especially untenable considering the significantly increased academic pressure on students, and the highly computerised nature of the education process, which demands even higher levels of illumination quality. At the same time, with growing urban building densities the use of natural light in classrooms is decreasing, and many classrooms are permanently using combined illumination (daylight with artificial illumination).

The issues described above are fully applicable to higher education institutions, which many young people graduate from some sort of sight pathology (already 30–32 %).

Based on these facts, the following actions are advised:

1. To carry out the lighting energy audits of schools and the state of their illumination;

2. To address the question of improvement of illumination in schools, nurseries and other education centres at the Department of Education. To prepare and validate an integrated programme of modernization for illumination devices in schools, with allocation funding;

3. This programme should include the following:

– To carry out lighting and health impacts researches of illuminating educational institutions with new effective illumination facilities, especially to examine the impact of light emitting diode ultra-violet radiation on children's sight;

– To select the most appropriate designs of modern luminaires with highly economical light sources for comfortable illumination, and of devices for ultra-violet sanitary radiation;

– To equip a number of Moscow schools as demonstration sites, with exemplary illumination devices meeting all the standards, with energy saving light sources and light devices;

4. To decree a Moscow Government order, which prevents new and refurbished buildings from being signed off for use unless they meet relevant illumination standards.

As a conclusion, I would like to stress that pushing Russian lighting industry and science up to global modern standards can only be done with significant investment. Without investment, raising product quality requirements, improving in certification, instigating legislative drivers, and all of the other necessary measures mentioned above will not only fail to reduce import dependency, but are more likely to lead to the contrary outcome: further reduction of domestic production's market share and an increased volume of foreign products, far from the best on the market. Catching up with the best foreign "trains" speeding ahead during this period, becomes more and more challenging and less and less likely. Only immediate steps towards establishing co-production with leading foreign companies interested in the immense Russian market, can provide such a possibility, though still slim. This partnership approach is the only realistic direction in the absence of tangible investments, which seem almost incredible in today's conditions.

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USER EVALUATION OF PEDESTRIAN WAY LIGHTING

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ABSTRACT

The aim of the study was to find out user preferences for pedestrian way lighting under different lighting conditions. The illumination conditions of the lighting installations were judged by the users. There were five different luminaires in the study, three LED luminaires and one luminaire with a metal halide (MH) and one with a high pressure sodium lamp (HPS). The electrical and luminous characteristics of the luminaires were measured in the laboratory and horizontal and semi-cylindrical illuminances on the road. A user survey was carried out with 46 people. The respondents liked the tone of the light when the correlated colour temperature CCT was around 3000 K and they liked the illumination when the surroundings of the road were well illuminated.

Keywords: LED luminaire, outdoor lighting, user survey

INTRODUCTION

LEDs are becoming increasingly more widely used in outdoor lighting, especially in pedestrian way and park lighting. Due to the large variation in the quality between different LED solutions and also the difference of LED lighting when compared to conventional lighting solutions, it is difficult for the public authorities to evaluate the luminaires for the future purposes. The luminaires´ performance is affected by its optical, electrical and thermal characteristics, and it also has to fulfil the specific application requirements given by the lighting recommendations. Finally, user preferences are also important. The aim of the study was to find out correlations between the technical characteristics of the luminaires and lighting installations and the results from the user survey. The results were to be used for recognising the relevant photometric characteristics of luminaires. In this study there were three different LED-luminaires used along with more conventional light sources, namely tubular high pressure sodium lamps and metal halide lamps. The luminaires were first measured in the laboratory and then installed in a pedestrian way in Helsinki. Four pieces of each luminaire were installed in the pedestrian way that was commonly used by cyclists, runners and pedestrians. After the installation the lighting conditions of all five pedestrian way sections were measured. The total length of the pedestrian way was approximately 700 meters. Altogether 46 people filled in a questionnaire form in the survey.

The driving forces for using LEDs in outdoor lighting are energy savings and reduced maintenance costs, but at the same time the LED luminaire installations should fulfil the lighting recommendations and standards and gain the acceptability of the users. Boyce et al. have found that there is a trend, where most of the views for the statements that were used in their study to evaluate the lighting conditions, tended to change similarly all together. The results of the Boyce study imply that good lighting is perceived to be bright, even, comfortable, non-glaring, extensive in area and well-matched to the site [1].

A field study on pedestrian ways with HPS and ceramic MH lamp based luminaires, showed, that white light was preferred over yellowish light, as the perception of brightness, comfort and safety were significantly higher under white light [2]. In the UK, a proposed guidance for lighting in residential roads has been published, with the aim to change the lighting recommendations of the S-classes. This proposed system allows a reduction in illuminance, specified using the CIE system of mesopic photometry, when lamps with Ra≥60 are used in the luminaires [3]. The reduction of the illuminance level of the S-class is based on the comparison of the scotopic/photopic-ratios of the benchmark light and the used light source (R_a≥60), where the benchmark light source is determined to be low pressure sodium lamp [3].

The use of lenses or lens matrices in the luminaires instead of reflectors has changed the optical characteristics of the luminaires. With a combination of LEDs and lenses it is possible to direct the light precisely on the road surface leaving the surroundings of the road in the dark. Due to this, the relevance of the lighting conditions on the verge of the road was examined in this study, and one of the questionnaire statements was dealing with it. The verge meant the surrounding areas near the road in our questionnaire.

METHODS

The photometric, optical and electrical characteristics of the luminaires were analysed in the laboratory by measurements using an integrating sphere, a goniophotometer and a digital power meter. The ambient temperature of the room was 22 °C. The luminaires were stabilized for one hour before the measurements. Each LED luminaire were measured, but only one MH and one HPS luminaire. The luminous intensity distribution curves of the luminaires were measured with a goniophotometer in C-γ-planes [4]. The C-planes were measured from 0° to 360° with five degree intervals, while the gamma-planes were measured from 0° to 90° with two degree intervals.

The measured luminous flux of the luminaires and the luminous intensity distribution data were later used in the lighting simulation program Dialux. The pole height and distance between poles were fixed since it was an old installation. Lighting simulations were used to check the adequacy of the luminaires for the road and at the same time the optimal angle of the luminaire to the horizontal plane was determined. For the high pressure sodium (HPS) and metal halide (MH) lamp luminaires the luminous intensity distribution curves were provided by the luminaire manufacturers and these data were used for the simulations.

After the laboratory measurements, the luminaires were installed by a pedestrian way located in the north-west of Helsinki. The width of the pedestrian way was four meters, the surface was sand and the verge of the road was mainly grass fields without any bigger obstacles like trees or bushes. The pole height was five meters and the pole spacing approximately 30 meters. Four luminaires of each luminaire type were installed in four consecutive poles. The installations were made at the end of June and were lit normally when required. After four months, in the middle of November, the lighting conditions were measured and the users were interviewed for the survey. The lighting conditions measurement included horizontal illuminances and semi-cylindrical illuminances. The measurement grid was determined according to the standard EN 13201–3 [4] and it was set to be the area between the second and the third pole of each luminaire set. In both cases the measurement grid was 3 x10 points, with three points in transverse direction (0.67 m, 2 m, 3.33 m) and ten points in longitudinal direction (1.5 m, 4.5 m, 7.5 m,..,28.5 m) of the road. The horizontal values were measured at the road surface and the semi-cylindrical values from 1.5 meters above the road [4].

The user survey was executed in the test site in November in one evening. Totally, 46 persons participated in the survey. There were 2 participants under 20 years, eighteen in range 21–30, ten in 31–40, nine in 41–50, 3 in 51–60 and none over 60. The proportion of the participants that used glasses was ~63 %. The questionnaire was first explained to every participant and after that they walked by themselves to the other end of the test road while evaluating lighting conditions. The statements were: S1-*There is enough light*; S2-*A tone of the light is pleasant*; S3-*Illumination is not glaring*: S4-*There is enough light on the verge of the road*. For the four statements they were asked to give their rating on a five-point scale, where one means that the statement was totally disagreed and five that it was totally agreed. The fifth question was about the general evaluation and it was rated from four to ten as the school grade ratings in Finland.

MEASUREMENTS

Photometric and electrical values of luminaires

In the following, the LED luminaires are denoted as LED1, LED2 and LED3, and the discharge lamp luminaires as HPS and MH. The luminaire case

Table 1. Means of photopic and electrical characteristics of different luminaires

Set	U, V	I, mA	P, W	pf	Φ_v, lm	η, lm/W	CCT, K	R_a
LED1	230.5	181	38.4	0.92	2950	77	4220	68
LED2	230.5	181	38.5	0.92	2070	54	2960	84
LED3	230.5	156	33.8	0.94	2650	79	3980	69
MH	229.9	299	63.9	0.93	3770	59	3300	72
HPS	229.9	311	66.4	0.93	3570	54	1880	23

U is supply voltage, I is current, P is total power, pf is power factor, Φ_v is luminous flux, η is luminous efficacy, CCT is correlated colour temperature and R_a is CIE general colour rendering index

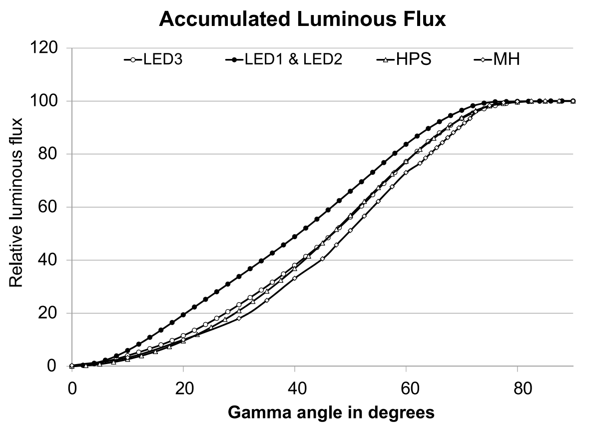

Fig. 1. Cumulative luminous fluxes for each luminaire type

for both of these sources (HPS and MH) was similar. Also LED1 and LED2 were optically similar to each other, however, the spectral power distributions (SPD) and luminaire luminous fluxes were different. Four pieces of LED1 and LED2 luminaires, six pieces of LED3 luminaires and one piece of HPS and MH luminaires were measured. The mean values of the measured photometric and electrical characteristics of each luminaire type are shown in Table 1.

Luminaire luminous intensity distribution

The relative and the actual values of the maximum luminous intensities are shown together with the direction of the maximum intensity in C-plane and in γ–angle in Table 2. Due to the spatial distribution of the LED1 and LED2 luminaires, in the installation setup the boom angle was set to the 20 degrees in these cases while the other luminaires were installed in the horizontal position. The luminaire efficiencies of HPS and MH luminaires were given by the manufacturer, the values for both luminaires being 75 %. Efficiency of the HPS and MH luminaires was the luminous flux of the luminaire divided by the luminous flux of the lamp. Efficiency of the LED luminaires was set to be 100 % due to the measurement procedure, where actual luminous flux of an integrated LED light source could not be determined separately. The maximum luminous intensity varied from 1820 cd (LED3) to 3810 cd (LED1). The gamma angle of the maximum intensity varied from 56 degrees to 70 degrees depending on the luminaire.

The cumulative luminous fluxes are shown in Fig. 1, where the luminous flux of the luminaire is divided to the segments as a function of gamma. The graph shows that the LED1 and LED2 luminaires provide more light than LED3, HPS and MH luminaires to small angles. The LED1 and the LED2 luminaires provide half of their total luminous flux, in gamma angles smaller than 40 degrees, while the other luminaires provide around 35 % of their total luminous flux in these angles. If the gamma angle is smaller than 40 degrees, light from the five meter pole to the ground level is distributed within 3.2 meters from the pole. The graphs also indicate, that the luminaire luminous flux is basically provided to the gamma angles less than 75 degrees, which covers a circular area with a radius of 18.5 meters on the ground level. The distance between two poles was about 30 meters.

MEASUREMENTS ON-SITE

The illumination conditions on site were measured in autumn, when the nightfall was much earlier compared to summer, when the installations took place. The weather was clear and around 10 °C. The measurements were made with the same measurement grid of 3 x10 points. The results are shown in Table 3.

Table 2. Measured values of luminaire: luminous flux, efficiency, actual and relative maximum luminous intensity, and the angle of the maximum intensity

Set	Φ_v, lm	Efficiency, %	$I_{rel., max}$, cd/klm	I_{max}, cd	C-plane	γ-angle, degree
LED1	2950	100	1300	3810	C0-C180	56
LED2	2070	100	1300	2680	C0-C180	56
LED3	2650	100	670	1820	C160-C340	56
MH	3770	78	480	2320	C20-C200	70
HPS	3570	75	470	2240	C20-C200	70

The measured illuminances were evaluated according to the pedestrian way S- and ES- lighting classes provided in standard EN 13201 [5, 6]. The minimum maintained horizontal illuminance E_{min} for S3 is 1.5 lx, which is fulfilled by all the luminaire installations. The luminaires LED1 and MH also fulfilled the minimum limit of 3 lx of the S2 class. The minimum values for mean illuminances are 7.5 in S3 and 10 lx in S2. In all the installations, the minimum maintained mean illuminance of S2 and S3 were fulfilled. In the S-classes there is also an additional rule for the mean illuminance that defines the upper limit of mean maintained illuminance to the value of 1.5 times the limit of minimum maintained mean. In principle, LED2, LED3 and HPS provided the S3-class illumination, with an exception that the mean of LED3 was less than one lux too high. LED1 and MH provided the S2 class illumination, with an exception that the mean illumination of LED1 was too high.

Also, the illuminances of the test road were compared to the ES –classes, which give semi-cylindrical illuminances. The ES classes are intended as additional classes for pedestrian areas for the purposes of reducing crime and suppressing feelings of insecurity [6]. In the ES-classes only the maintained minimum values of semi-cylindrical illuminances ($E_{sc, min}$) are provided. Alternative class for S3 is the ES6-class, which requires that maintained $E_{sc, min}$ should be 1.5 lx [5, 6]. This minimum value was not reached in any of the installations, and even the lowest class ES9 requirements of 0.5 lx was achieved in only three luminaire sets, which were LED1, MH and HPS. The reason for this is the relatively low pole height (5 m), while the pole spacing was relatively long (30 m).

The semi-cylindrical illuminance is a value that is mainly used for the evaluation of facial recognition. In former studies it has been found that the level of semi-cylindrical illuminance needed for facial recognition from four meters was either 0.6 or 0.8 lx. The recognition from ten meters needed either 2.7 or 3.4 lx depending on the study [7,8]. Upper limit of semi-cylindrical illuminance, where the distance of the recognition does not increase anymore, is around 25 lx. When the luminaire installations of this study are compared to these values, the minimum values of MH and HPS barely fulfil the values

Table 3. Maximum, minimum and mean horizontal and semicylindrical illuminances of the pedestrian way under the different luminaires

	Horizontal illuminance			Semicylindrical illuminance		
Set	E_{max},	E_{min},	E_{ave},	E_{max},	E_{min},	E_{ave},
	lx	lx	lx	lx	lx	lx
LED1	54.0	4.3	17.1	45.6	0.5	8.2
LED2	37.7	2.5	11.1	29.6	0.3	5.3
LED3	36.7	2.1	12	26.6	0.3	6.2
MH	35.1	3	12.2	20.2	0.6	6.7
HPS	31.7	2.1	10.5	27.0	0.7	7.8

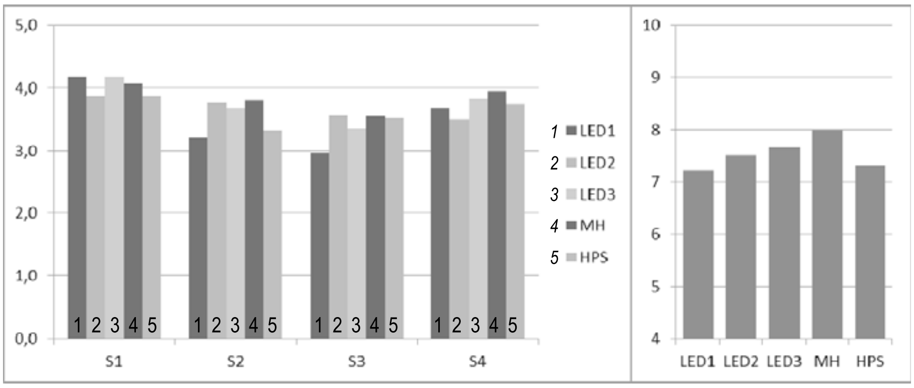

Fig. 2. Mean values and the standard deviations of the ratings given for the questionnaire statements S1, S2, S3, S4; rating was from 1 – disagree totally to 5-agree totally

required for the recognition from four meters, while the minimum value in the other sets stays below this limit. All the mean values of E_{sc} fulfilled the values that are required for the recognition from ten meters. The maximum E_{sc} values were more than 25 lx in every set except in the HPS and the highest value of E_{sc} ~45 lx was measured with the LED1 set.

The luminous flux Φ directed onto an area of the road was evaluated by multiplying the horizontal illuminance values E and the area of measurement A, since $E=\Phi/A$, so $\Phi=EA$. For the LED1 and the LED2 installations 70 % and 65 % of the total luminous flux was directed onto the road. The relative values for LED3, HPS and MH were around 55 %, 33 % and 40 % respectively. The rest of the total luminous flux was used to light side areas of the road.

USER SURVEY

The overall means and the standard deviations of the ratings given in the questionnaire are presented in Fig. 2. The rating scale for the four statements was from 1 to 5. The mean rating for the first statement ("There is enough light") was 4.0 with a standard deviation of 1.1. The mean rating for the second statement ("The tone of the light is pleasant") was 3.6 with standard deviation of 1.1 and for the third statement ("The illumination is not glaring") these values were 3.4 and 1.2 respectively. For the fourth statement ("There is enough light on the verge of the road"), the overall mean rating and the standard deviation were 3.7 and 1.3 respectively.

In addition to the four statements, the people gave an overall mark for each installation by the Finnish school grading system with gratings from 4 to 10. The luminaire sets were evaluated to match grades from good (8) to satisfying (7). The mean of the overall grades was 7.5. The highest mean grade, 7.9, was given to the MH installation and the lowest mean grade, 7.1, to the LED1 installation. The other installations, LED3, LED2 and HPS, were given grades 7.6, 7.4, and 7.3 respectively.

For the first statement dealing with the amount of light on the road, the highest ratings were given for the LED1 installation. People rated the statements in a scale from one to five, where one meant that the statement was totally disagreed and five that it was totally agreed. The ratings 4 and 5 were considered as positive opinions, and for the first statement the amount of evaluations for these ratings were 25 and 11, respectively. At the same time, the amount of the negative opinions, considered as ratings 1 and 2, were only five. The mean value for the LED1 installation was 4.17, which was the same mean that the LED3 installation had. In LED1 and LED3 installations, the LEDs were cool white sources. The lowest ratings were given for the LED2 and HPS installations; the mean was 3.87 for them both. Within the ratings the smallest standard deviation was found within the LED3 (0.95) and the largest within the HPS (1.20).

The second statement was dealing with the pleasantness of the tone of the light. Here, the MH installation was given 28 positive opinions and five negative ones; the mean of the ratings was 3.80. The mean ratings given for the LED2 and LED3 installations were 3.76 and 3.67, respectively. The lowest ratings were given for to the LED1 installation with 15 positive and 11 negative opinions and the mean value 3.20. Also for this statement the HPS installation (1.19) had the highest and the LED3 installation (0.95) the lowest standard deviation.

The third statement was "The illumination is not glaring". Here the LED2 installation was evaluated

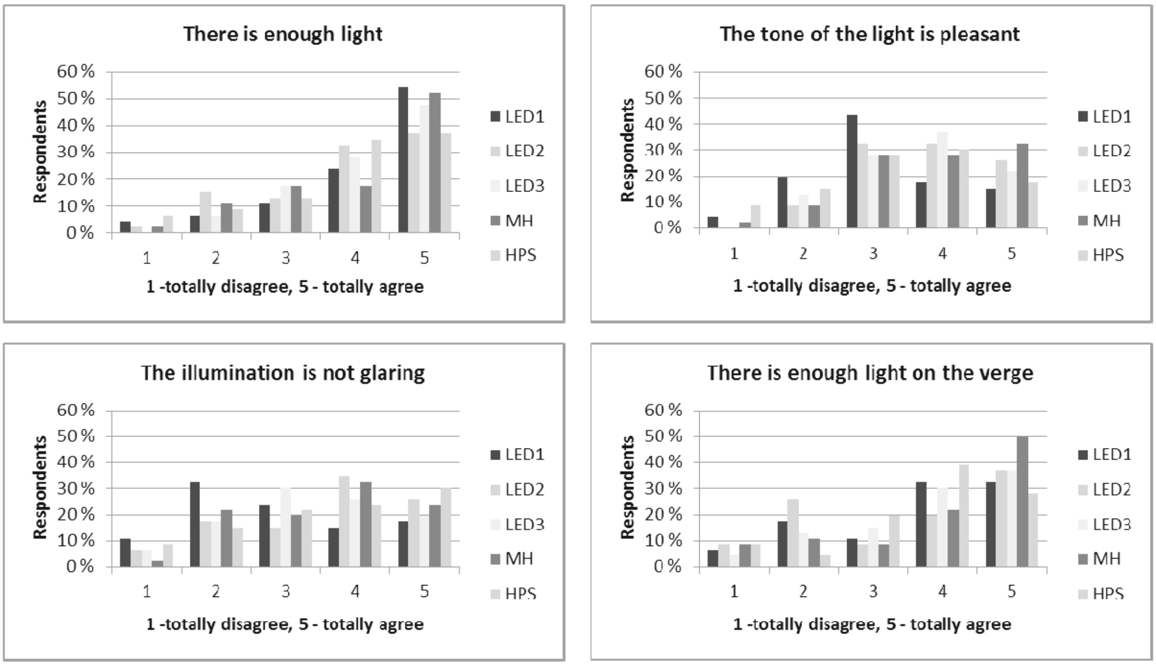

Fig. 3. Distributions of the ratings given for each statement

with the best scores, having totally 28 positive and 11 negative opinions. The mean of the ratings for this installation was 3.57, and for the MH and HPS installations 3.54 and 3.52, respectively. The lowest ratings were given for the LED1 installation with 15 positive and 20 negative opinions. The LED2 and the LED1 luminaires had a very similar luminous intensity distribution while the luminous flux and CTT were different. Luminous fluxes were 2950 lm and 2070 lm and CCTs 4220 K and 2860 K, respectively. The standard deviation of the ratings was highest for the HPS (1.31) and lowest for the MH installation (1.15).

The last statement was “There is enough light on the verge of the road”, where the highest ratings were given for the MH installation with 33 positive and 9 negative opinions, mean value being 3.93. The lowest ratings were given for the LED2 installation, with 26 positive and 16 negative opinions given, and the mean value being 3.50. The standard deviation was highest for the HPS (1.65) and lowest for the LED3 installation (1.33). The distributions of the ratings given for each statement are shown in Fig. 3.

The MH installation was evaluated with the highest and the LED1 installation with the lowest ratings for the overall grade. The mean value of the best overall grade was 7.9 (MH), while the lowest one was 7.1 (LED1). The mean overall ratings for the LED2, LED3 and HPS installations were 7.4, 7.6 and 7.3, respectively. For the overall grade, Fig. 4, the MH installation was given the highest scoring (10) totally 7 times. The smallest standard deviation of the overall grade was found for the LED3 (1.33) and the highest one for the HPS (1.65) installation. Both with separate statements and with the overall grading the LED3 installation seemed to divide the opinions of the people the least, while the opposite was true for the HPS installation.

The results of the survey were statistically analysed with IBM SPSS Statistics using multiple linear regression. This analysis was first made for all the installations together and then separately for each installation. In both cases the four statements (S1, S2, S3, and S4) were used as independent variables, which were compared with the overall grade as a dependent variable. The significance level was $p<0.05$.

When different installations were evaluated separately, not all the statements had statistically significant effect to the overall grade. In LED1 installation significant statements were S1, S2 and S3, in LED2 S1, S2 and S3, in LED3 S1 and S3, in MH S4 and in HPS S2. The results showed that respondents were focusing to the different things in different lighting conditions. For example, under the HPS installation the tone of the light was the only significant statement and under MH installation the illumination of the verge of the road.

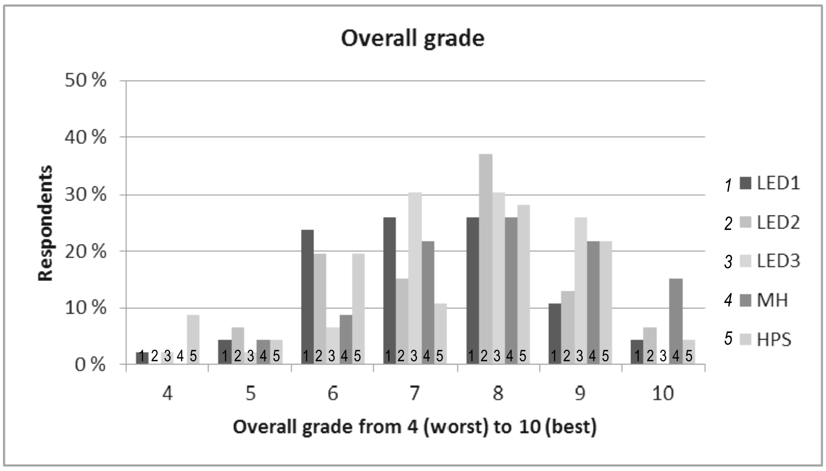

Fig. 4. The distribution of the ratings given for the overall grading

CONCLUSIONS

People evaluated the five different lighting installations by giving their rating to four statements and an overall rate for the illumination. The horizontal illuminance was between 10.5 lx and 17.1 lx and most of the people considered that there were enough light on the road (statement S1). The yellowish light (1880 K) from HPS lamp divided the opinions of the respondents, but also the coolest light from LED1 (4220 K) was given lower ratings. People preferred the light from LED2, LED3 and MH. The CCT from these luminaires were between 2960 K and 3980 K. LED1 was estimated to cause more glare than the other luminaires and LED1 got the lowest overall grade. The maximum luminous intensity of LED1 was 3800 cd, gamma angle was 56° and C-plane C0-C180. LED2 had similar spatial luminous intensity and the maximum intensity was in the same direction, but the maximum intensity was 2700 cd. Also the CCTs were different 2960 K in LED 2 and 4220 K in LED1. According to user survey LED2 did not cause glare. The MH installation got the highest rating for the statement S4 considering the illumination of the verge of the road. There were two luminaires in the study, where the calculated luminous flux directed to the surface of the road was less than 50 % of the total luminous flux. For HPS it was around 33 % and for MH it was 40 %. With these luminaires the actual amount of light outside the road was almost equal due to the higher luminous flux of the MH luminaires. MH got also the highest overall rating in the user survey.

The results showed that the spatial distribution of the luminous flux of the luminaire should be designed to give enough light on the verge of the road and to avoid glare.

There were huge differences in the luminaires used in this study, so there were also many variables affecting the opinions of the respondents. In future, certain properties could be examined separately so that the acceptance of the people is limited more exact to the certain properties. For instance, if luminaire is causing glare, it might be that it will affect also on people's opinion on the pleasantness of the tone of the light. Future user acceptance studies for LED lighting should focus on the tone of the light and the amount of light directed to the surroundings of the road, which characteristics are not included in the current lighting recommendations.

ACKNOWLEDGEMENT

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MEASUREMENTS OF ELECTRIC, PHOTOMETRIC AND COLORIMETRIC PARAMETERS OF LEDS USING AT DIFFERENT AMBIENT TEMPERATURES

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ABSTRACT

The paper presents the results of measurements and calculations of electric, photometric and colorimetric parameters of LEDs of different construction. Those parameters of LEDs have been measured at different ambient temperatures. The ambient temperature was changed from 25^0 C to -25^0 C by 5^0 C steps. All tested LEDs were supplied by a line voltage of 230 V and were equipped with E27, E14 and GU10 bases. Changes for following parameters as function of ambient temperature were registered: current, power, power factor, relatively changes of luminous flux as well as the relative spectral distribution function. On the basis of spectral distribution function colour temperature (T_c) and colour rendering index (*CRI*) were calculated. Chosen results of measurements and calculations are presented in the paper.

Keywords: electric sources, LED, ambient temperature, luminous flux, colour temperature, colour rendering index, power, power factor

1. INTRODUCTION

The construction of light emitting diodes (LED) is growing very fast. Applications of those new light sources are extending into very wide range of lighting areas in outdoor as well as indoor lighting. LEDs are used in different conditions where ambient temperature has an influence on their main electric, photometric and calorimetric parameters. The knowledge of main parameters dependence on ambient temperature is very important. The chosen types for test of LED retrofit lamps for testing are currently offered on the market. Many chosen results of measures and calculations of electric and photometric parameters of chosen LED lamps from all the measurements are presented in the paper.

2. SUBJECT AND SCOPE OF STUDY

LED retrofit lamps chosen for the test are typical in the market, supplied by line voltage (230 V), and equipped with typical bases E27, E14, and GU10. The main electric and photometric parameters of the chosen LED lamps are shown in the Table1.

3. EQUIPMENT FOR RESEARCH

Registration of electrical and photometric parameters, as well as registration of the spectral distribution curves of semi-conductor light sources was conducted by means of a thermal test chamber, in which the tested light sources were placed. A schematic diagram of the measuring system is presented in Fig. 1.

Light sources *(6)*, by means of power switches *(1, 5),* were fed on a voltage stabiliser *(2)*, which provided constant rms voltage with an accuracy of 0.1 %. By means of the autotransformer *(3)* the value of 230 V was set. Individual electrical parameters are reg-

Table 1. General technical information of tested LED lamps

No.	*U*, V	*I*, mA	*P*, W	Base	Colour	*CRI*	*Φ*, lm	Time-life, h	Beam angle, Degree
1.	230	45	2.0	E27	x	x	x	x	x
2.	230	x	1.5	GU10	cool white	x	100	20000	150
3.	230	x	1.5	GU10	warm white	x			
4.	230	x	1.5	GU10	warm white	x	65	20000	60
5.	220–240	31	1.8	GU10	3000 K	> 70	150	25000	120
6.	220–240	31	1.8	GU10	6 400 K	> 70	150	25000	120
7.	230	x	1.5	GU10	cool white	x	110	20000	150
8.	230	x	5.0	GU10	warm, 827	≥ 80	350	30000	120
9.	220–240	x	x	E14	x	x	x	x	x
10.	230	x	9.0	E27	3 000 K	x	x	x	x
11.	220–240	x	12	E27	2 700 K	90	810	25000	x
12.	85–265	x	3	E27	warm white	x	210	20000	120
13.	230	x	0.67	E14	red	-	x	25000	12
14.	220–240	x	1	E14	blue	-	x	25000	12
15.	230	x	0.82	E14	green	-	x	25000	12

x – the information is not available

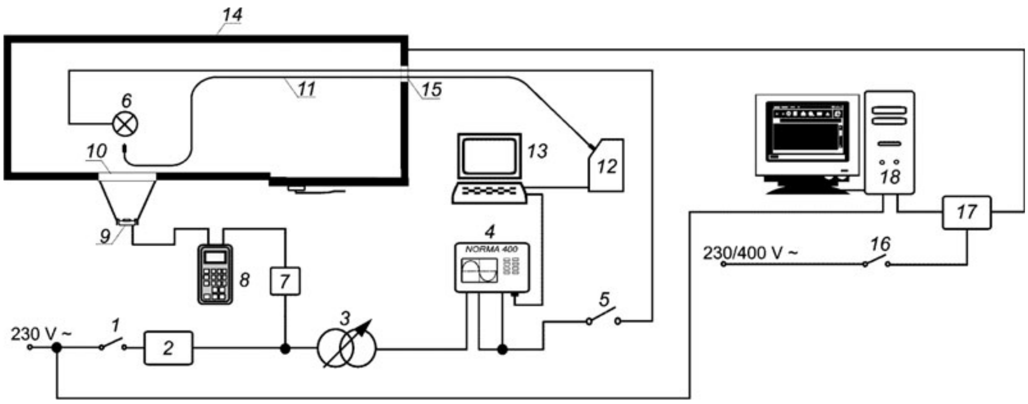

Fig. 1. Schematic diagram of the measurement system

1, 5, 16 – power switches, *2* – voltage stabiliser, 3 – autotransformer, *4* – power analyser, *6* – tested light source, *7* – external power supply integrated with illumination meter, *10* – circular glass enabling observation, *11* – opitical fibre, *12* − spectrometer, *13* – PC for spectrometer, *14* – environmental test chamber made of sandwich panels, *15* – culvert, *17* – chamber control unit, *18* – PC controlling the chamber

istered by the power analyser *(4)* integrated with a PC *(13)*. Photometric parameters are controlled by a photometric head *(9)* connected to the control unit of an illumination meter *(8)*, which is fed by the external power supply *(7)*. A photoelectric cell was permanently fixed to the apex of the cone, which was mounted to the external side of the circular glass *(10)* (the one from the thermal chamber). It measures luminous intensity in a selected direction. If one assumes that shapes of photometric forms of the tested light sources are constant (not dependent on the ambient temperature), then the measurement values registered by the illumination meter represent relative changes of luminous flux. The meters (power analyser and illumination meter) were connected to the PC by a RS-232 C serial communication cable. Optical fibre *(11)* introduced to the inside of the thermal chamber *(14)* through the culvert *(15)* provides a

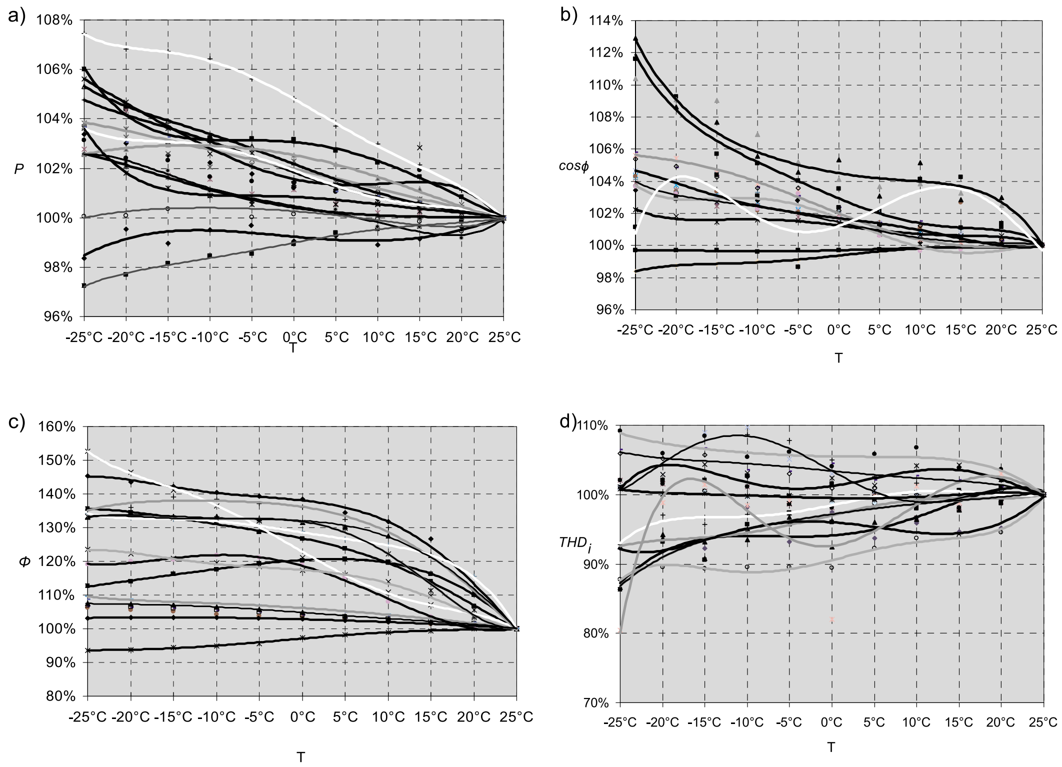

Fig. 2. The temperature dependence of: a) power, b) power factor, c) luminous flux, d) relatively changes of THD_i as a function of ambient temperature

measurement signal (light) to the spectrometer *(12)*, which is placed outside. Communication between the spectrometer and the PC takes place by means of a USB 2.0 interface. Registration of individual parameters of the tested LED lamps was taken after 20 minutes of their operation. During measurements, all the light sources were placed vertically (their longitudinal axis was perpendicular to the circular glass). The process of temperature regulation inside the research area was controlled by the PC *(18)* and operated by a PLC driver *(17)*. Measurements started at 25^0 C, which was taken as a reference temperature.

4. RESULTS OF MEASUREMENTS AND CALCULATIONS

4.1. Relative changes of electric and photometric parameters as a function of ambient temperature

The influence of the ambient temperature on chosen LEDs lamps measured parameters such as power, current, power factor and luminous flux is shown in Figs. 2 and 3. Fig. 2 a is for power, Fig. 2 b – for power factor and Fig. 3 c – for luminous flux in relative units. The ambient temperature has been changing from –25 ^oC to 25 ^oC. The results are concerning for 15 LED lamps.

The changes of THD_i and current time characteristics as a function of ambient temperature were tested. The relatively changes of THD_i as a function of ambient temperature are shown in Fig. 2 d. The ambient temperature has been changing from –25 ^oC to 25 ^oC. The results are concerning for15 LED lamps.

4.2. Changes of spectral distribution

The ambient temperature of LED has no critical influence on the spectral distribution shape. The change is concerning the value of power distribution and it is consequence of the temperature influence on LED power. There are two spectral characteristics (for LED numbers 2 and 3) measured at three ambient temperatures 25 ^oC, 0 ^oC and – 25 ^oC are shown in the Fig. 3.

4.3. Changes of T_c and *CRI*

The changes in colour temperature and colour rendering index for three LEDs are shown in the Fig. 4. There are samples of changes T_c and *CRI*

Table 2. The changes in chosen parameters of LED lamps as a function of ambient temperature

No.	*P*, W		Δ*P*, %	*THD*$_i$, %		Δ*THD*$_i$, %	*CRI*		Δ*CRI*, %	T_c, K	
	25 °C	-25 °C		25 °C	-25 °C		25 °C	-25 °C		25 °C	-25 °C
1.	1.95	2.01	3.1	25.1	23.1	-8.0	73.5	72,6	-1.2	2923	2885
2.	2.29	2.43	6.1	205.7	177.5	-13.7	80.1	78.2	-2.4	7550	7292
3.	2.45	2.51	2.4	196.1	181.3	-7.5	74.9	75.0	0.1	3272	3283
4.	1.62	1.69	4.3	25.7	22.6	-12.2	64.4	64.0	-0.6	3330	3281
5.	1.98	2.04	3.0	32.1	32.8	2.1	70.8	71.3	0.7	3092	3110
6.	1.82	1.88	3.3	32.1	32.8	2.1	71.8	69.5	**-3.2**	6828	6635
7.	3.19	3.43	7.5	142.3	132.0	-7.2	82.2	82.7	0.6	3027	3064
8.	3.36	3.54	5.7	32.8	34.9	6.4	73.1	73.2	0.1	2765	2776
9.	5.31	5.32	0.2	55.3	58.6	6.0	66.4	66.1	-0.5	3260	3178
10.	8.43	8.29	-1.7	67.0	67.7	1.1	66.5	66.7	0.3	3087	3025
11.	13.72	13.34	-2.8	29.4	29.7	1.0	66.5	66.7	0.3	3077	3025
12.	2.86	2.93	2.4	217.7	188.4	-13.4	61.3	61.2	-0.1	3106	3022
13.	0.86	0.91	**5.8**	23.4	23.6	1.0	x	x	x	x	x
14.	0.74	0.76	2.7	29.4	23.6	**-19.6**	x	x	x	x	x
15.	0.55	0.56	1.8	26.3	28.7	9.2	x	x	x	x	x
x – not applicable, numbers in bold – the greatest changes											

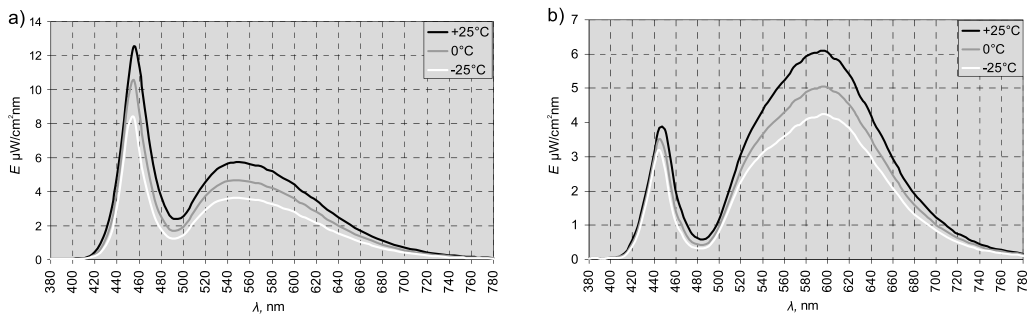

Fig. 3. The changes of spectral distribution in function of ambient temperature for two LEDs, nb a) 2 and b) 3

in dependence with ambient temperature presented in Fig. 5, for three chosen types of LED lamps. The ambient temperature has been changed from –25 °C to 25 °C. The results concerning the three chosen LED lamps, nb. 1, 2 and 3, are presented in Table 3.

4.4. Changes of chosen parameters of LEDs as a function of ambient temperature

The changes in power consumption *P*, total harmonic distortion *THD, colour rendering index CRI*, and colour temperature T_c as a function of ambient temperature are shown in Table 2.

5. CONCLUSION

On the basis of laboratory measurements of the main electric, photometric and colorimetric parameters for chosen samples of LED retrofit lamps as a function of ambient temperature the following conclusions can be drawn:

- At constant supply, electrical, photometric and colorimetric parameters of LEDs are a function of temperature.
- The presented data show that the luminous flux is the most ambient temperature dependent parameter (from the results for all measured LED lamps).
- The relative changes of luminous flux value reach up to 50 % at an ambient temperature in the range 25 °C do – 25 °C. For all of tested LEDs (excluding the nb 14) the value of luminous flux is increasing when the ambient temperature is decreasing.
- For most of the tested light sources an increase of power, power factor and total harmonic distor-

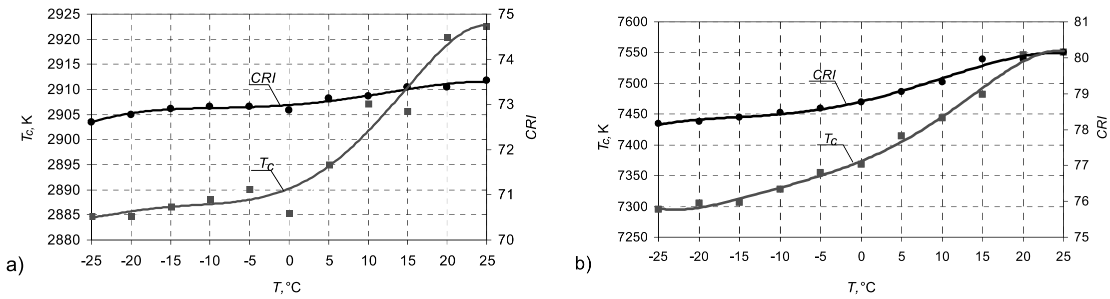

Fig. 4. Changes of T_c and *CRI* as a function of ambient temperature for temperature for two LEDs, nb a) 1 and b) 2

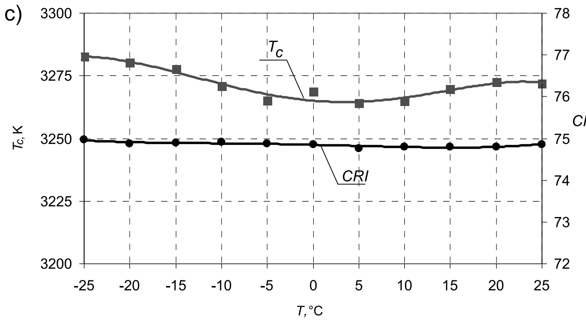

Fig. 5. Changes of T_c and *CRI* as a function of ambient temperature LED lamp nb 3

tion is observed. The changes of power and power factor are the preferred from quality of electricity viewpoint.

- T_c and *CRI* are of little significance in dependence from ambient temperature. The relative changes of those parameters are less than 5 % in the temperature range (+25 °C) – 0°- (– 25 °C).

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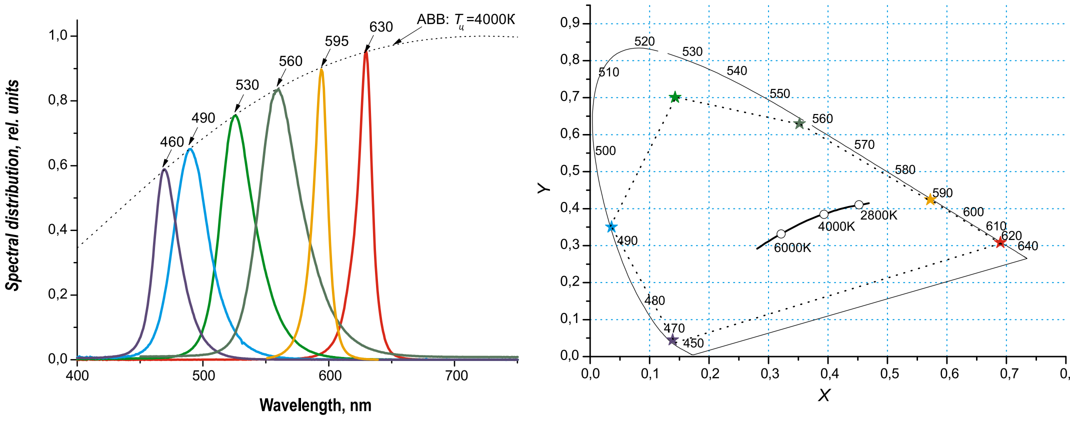


Fig. 1. Spectra of six light emitting diodes used for colour mixing (envelope curve – ABB spectrum with T_{c} = 4000 K), (a) and chromaticity coordinates of these light emitting diodes on the CIE 1931 colour diagram (b)

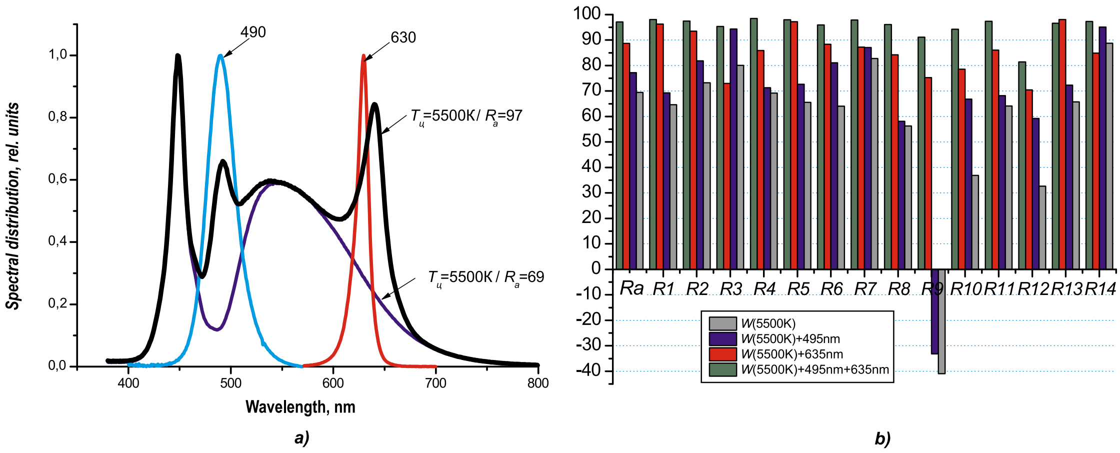


Fig. 2. Spectra (a) and colour rendering indices R_a and R_i (b) of white LED with T_c = 3200 K based on a phosphor white light emitting diode with additional correction using phosphor-free light emitting diodes with λ_{max} = 490 and 630 nm

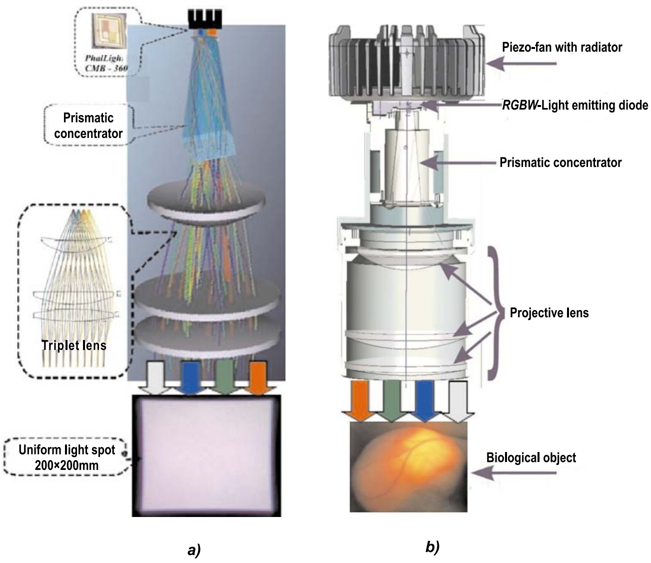


Fig. 5. Optical system (a) and structural view of main units (b) of the operational luminaire

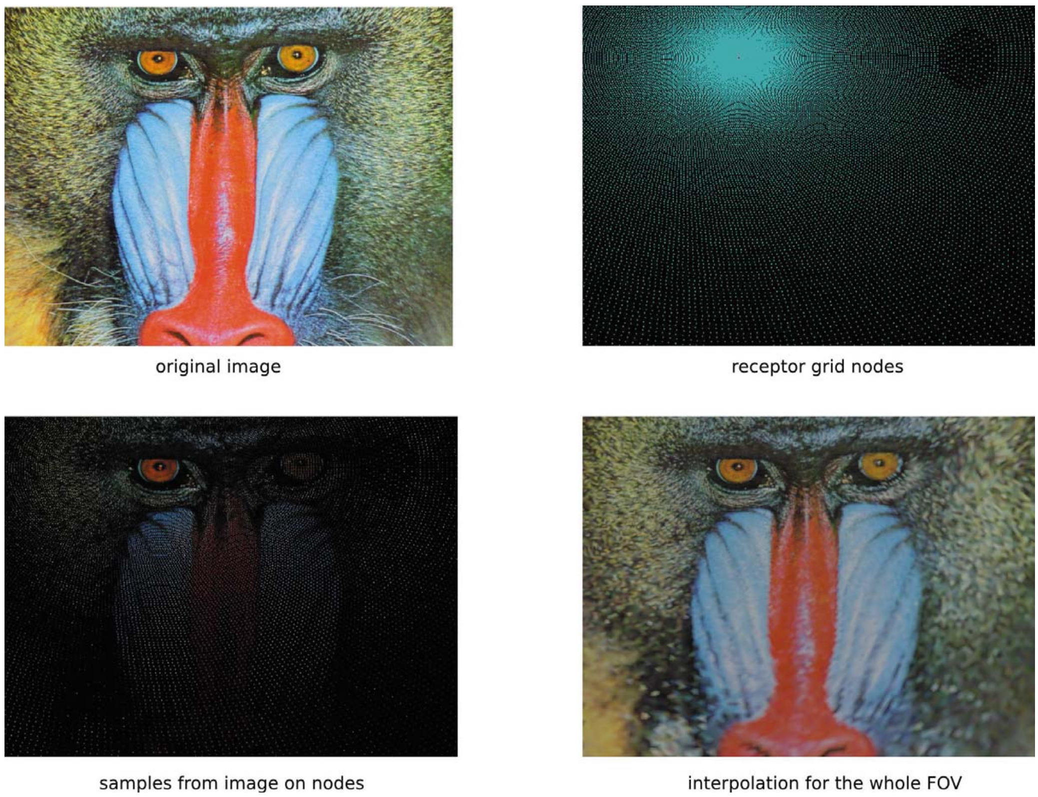


Fig. 1. Demonstration of sampling and interpolation steps with a sparse grid

Fig. 3. Looking at second traffic sign (from the left) with normal and half acuity vision

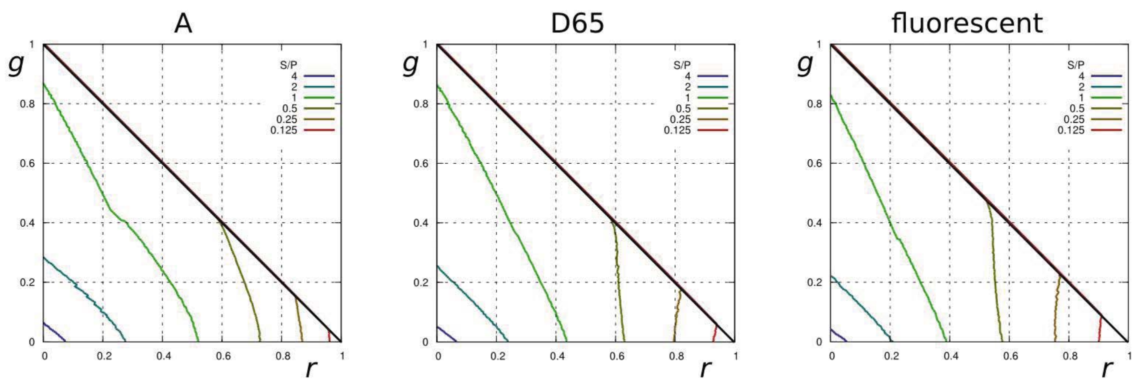


Fig. 4. *S/P* as a function of chromaticity coordinates with different light sources

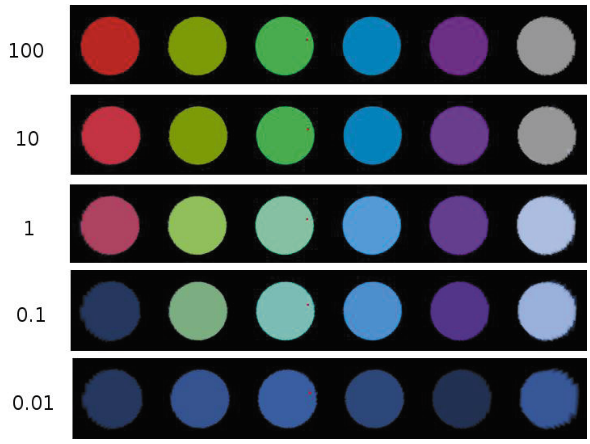
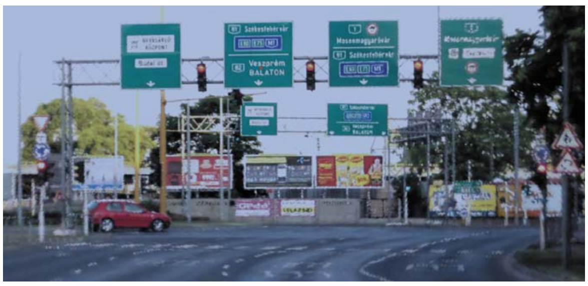


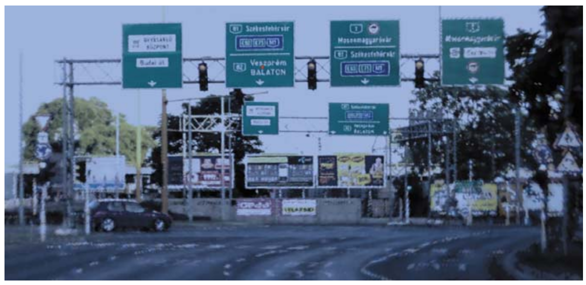
Fig. 5. Simulation of vision of a disc series with different L_0 [cd/m^2] values

$L_0 = 1\mathrm{cd/m^2}$ $L_0 = 0.01\mathrm{cd/m^2}$

Fig. 6. Baboon test image at high and low mesopic range



L_0 =1.0



L_0 =0.1

L_0 =0.01

L_0 =0.001

Fig. 7. Simulation of mesopic vision in a traffic situation for different L_0 values

Fig. 2. Ionic-plasma cleaning unit

Fig. 3. The stencil process printer

Fig. 5. Chamber type dryer

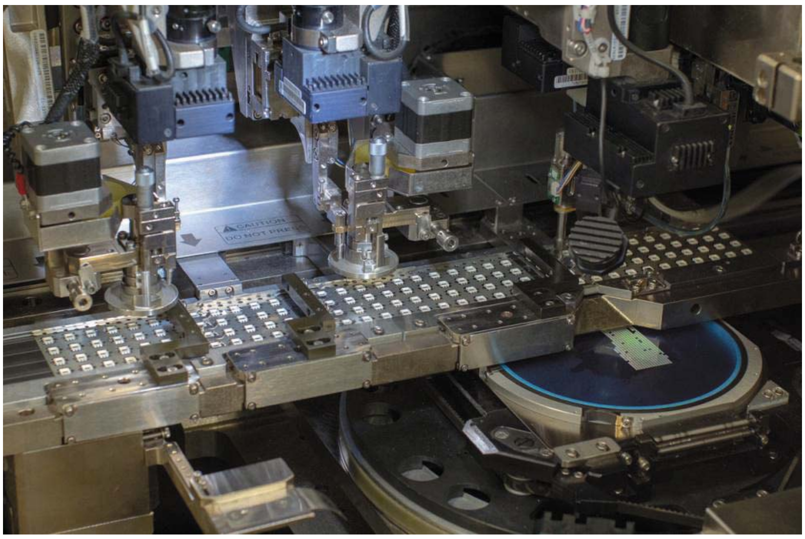


Fig. 4. Deposition of joining material by printing and crystal mounting

SPECTRAL DEPENDENCE OF VISUAL FUNCTIONS WHEN COMPARING CHARACTERISTICS OF WHITE LIGHT EMITTING DIODES

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ABSTRACT

Basic physiological data are presented, which show that artificial sources of warm-white light with a solid spectrum are preferable for daily used. Conversely, artificial light sources with a superfluous dark blue component and a discrete spectrum are tiresome and potentially unsafe.

Keywords: spectrum, visual acuity, light hygiene, eye risks, energy saving lamps

Natural daylight is a generally accepted reference for quality of light. During a day, illumination has a different level ratio within spectral intervals of 380–480 nm and 480–680 nm, which we will refer to as conditionally blue and conditionally yellow intervals (CBI and CYI) respectively. Morning and twilight light is more yellow, and midday light is more dark blue [1]. As a result, about two thirds of daylight constitutes warm white light. The human physiological schedule, developed throughout history, suggests that working time is mainly in the hours before and after the middle of the day, with a break for a midday "siesta", when cold white light prevails. In other words, human sight developed over hundreds of thousands of years, is adapted to illumination from warm white light.

The human eye has the following characteristics.

1. CBI is the "working" area of the blue-sensitive cones, and CYI is green- and red-sensitive. In the process of colour discrimination, blue-sensitive cones take part in blue-green shade evaluation, and other colours are mainly recognised by red- and green-sensitive cones.

2. Radiation within CBI is essentially more dangerous for the eye retina than within CYI [2–5].

3. Sleep and wake mode control is carried out with participation of blue-sensitive melanopsin ganglionic retina cells according to balance of the CBI and CYI illumination component ratio [6].

4. CBI radiation affects images at the eye fundus (a raised light diffusion on the eye's optical mediums and blurred focusing of dark blue light due to the chromatic aberration), and this significantly decreases visual acuity, more than a longer wave radiation. In addition, an excess of dark blue light reduces other parameters accompanying visual acuity, such as spatial contrast sensitivity and stability of distinct vision [7, 8].

5. Focusing within CBI demands a maximum laxation of the muscle around the crystalline lens to compensate for about 1.5 additional diopters (because of the difference of focusing dark blue and yellow light) [8].

Overall, the most vital visual problems of visual acuity and contrast sensitivity (distinction of small objects and of image contours) are solved by the fovea as the central area of the retina's acute eyesight, in which blue-sensitive cones are absent. Moreover, foveal red- and green-sensitive cones are screened against light in the 410–480 nm band with a yellow macular retina spot weakening this light by 4 to 10 times, depending on the individual properties of the eye. The central retina area is therefore blue-blind [9], and visual acuity does not need the dark blue component of the light source spectrum [7, 8]. Simplified, this property of the central

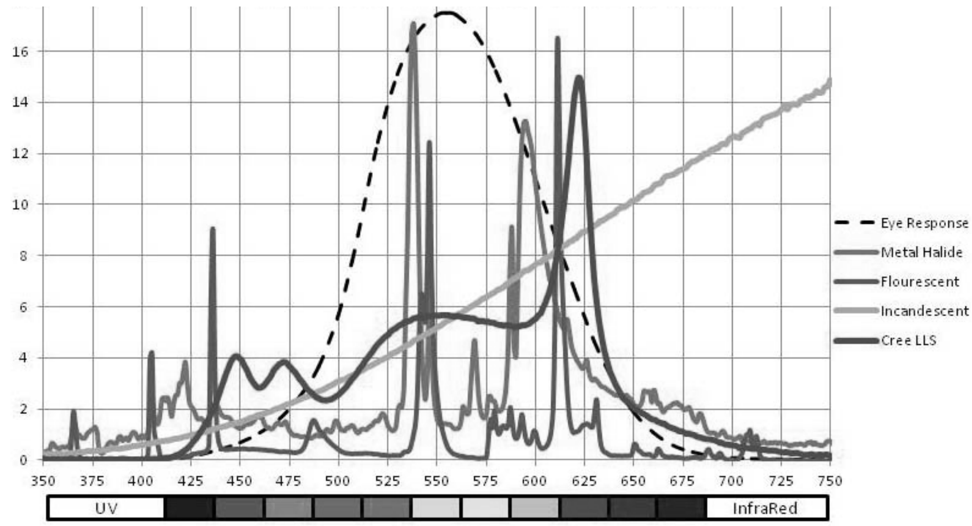

Fig. 1. Examples of spectra for four types of light sources against the background of a dotted curve of function V (λ)

sight is shown by the *V (λ)* function, which denotes weak eye sensitivity within the CBI. When interpreting colour, blue-sensitive cones are necessary to distinguish blue-green shades, which is not required often under living conditions. All other colour range discrimination is carried out within the CYI by means of red- and green-sensitive cones[1].

Over the last century, humankind has equally used both ILs (with T_c of about 3000 K), which are comparatively close to natural daylight by their spectral composition, and FLs, which vary by their spectra. Extensive ophthalmology and ergonomic research at the beginning of the twentieth century, as well as global practice and application led to a natural selection within the use of these lamps: ILs took root in domestic use, and FLs occupied the commercial and industrial sectors. The main cause of this separation consists in a different physiological perception of these illumination sources based on differences in their spectral radiation composition.

Currently, many societies are urged to forego traditional ILs and switch to more energy efficient light sources, such as FLs (CFLs) and LEDs. It should be noted that among FLs and LEDs manufactured today, there are many products which are close in their spectral composition to ILs, not to mention HILs. At the present time, practically all LED manufacturers are able to produce LEDs, which are spectral analogs of ILs. As an example, in Fig. 1, a spectrum of *LLS* series LED lamp made by *Cree* Company is given. Among modern FLs, there are lamps relatively close to ILs by spectrum.

At the same time, this article believes that cold-white and even neutral-white LEDs should not be adopting for domestic use. The argument that these LEDs are better by luminous efficacy is indefensible, because dark blue colour is useless, and probably dangerous for eyes. In our opinion and according to the conclusions of European expert groups [2–4], daily use of artificial light sources with a high dark blue component represents an unpredictable danger of early onset age sight loss. However, for the present, experimental data, which would allow predicting remote risks of the dark blue component of daily long-term illumination, are completely absent. Similar data obtained using monkeys and other animals and taken as a basis for light safety standards; this effectively presumes valuing risks for tomorrow based on reactions to strong short-term flashes [3–5]. According to these experiments, small blind spots within the vision field, because of partial destruction of the retina cells and of the retina pigment epithelium are appearing. It is going on after one or two days of irradiation by monochromatic radiation (dark blue) with $\lambda \approx 450$ nm for approximately 30 minutes at a radiant exposure (RE) of 30–50 J/cm^2 on the eye surface. As a comparison, radiation within the 500–650 nm range exerts an equivalent damaging action at RE ≈ 1000 J/cm^2 (Fig. 2). Based on assumptions drawn from these results, we can work out that reading a book for eight hours using light emitting diode illumination with $T_c \approx 6500$

[1] Examples of blue-green colour discrimination are relatively few and have, as a rule, a narrow field of application (for instance, car body paint or facial make-up).

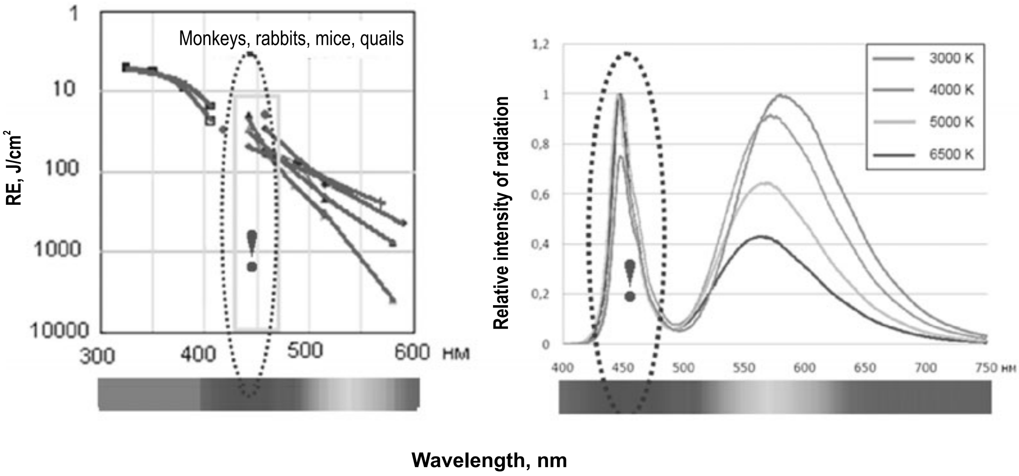

Fig. 2. Spectral dependence of radiant exposure (RE) of a retina photodamage for four kinds of animals and birds [5] (a) in comparison with spectra of white LEDs with different correlated chromatic temperatures [10] (b)

K and about 500 lx illuminance, RE within CBI obtained by a retina, is three times lower than the known photo damage threshold-discriminated RE. However, the effect after several years and even in a month under daily use of moderately blue light of a lesser intensity isn't known. Mice experiments [11] have shown that keeping the animals at weak illumination using LED luminaires of cold-white light during two hours a day and with RE ≈ 2,5 J/cm^2, leads to 30 % visual cell death in a month, and in ten months – to destruction of more than half of the cells. Quail (*coturnix japonica*) experiments (an experimental model of the accelerated aging of eye retina) have shown that photodamaging eye flashes appreciably accelerate senile changes in the retina pigmentary epithelium at the beginning and at the middle of the bird's life [12]. In other words, there are objective and of probable delayed risks in case of daily use of lamps with a superfluous dark blue component. Ultimately, nobody knows today whether using such an illumination is dangerous or not. We know, however, that light damage can accumulate with age; children's eyes are twice as sensitive to "dark blue" damage than adults. Elderly people fall into the higher risk group for age blindness, which is stimulated by dark blue light. The degree of an individual eye's protection against dark blue light can differ 10 – 15 times depending on personal and age properties. Therefore, in our opinion and according to the conclusions of European experts, uncontrolled use of cold-white and neutral-white LEDs can be potentially dangerous for the eyes [2–4]. Based on known physiological data, visual work using LED illumination with T_c > 3500 K appears to be appreciably more tiresome than IL illumination or using their LED spectral analogs. We do not see any reasonable preferences to use cold- and neutral-white LEDs in comparison with the warm-white. Manufacturing luminaires with cold-white LEDs with simple additions such as yellow light diffusers limiting the dark blue radiation component, could provide a simple mitigation of the risk of sight damage.

CONCLUSION

According to the article, the following conclusions can be drawn:

1) For everyday household use, luminaires with T_c of approximately 2800 K and solid, sufficiently uniform spectrum are appropriate and recommended; safe luminaires can be manufactured with warm white radiation using existing FLs and LEDs.

2) It is possible to agree with the European experts concerning the need for further research among the population, manufacturers of energy saving luminaires and ophthalmologists regarding safety of luminaires for domestic use. Marking light sources with T_c indication is not sufficiently informative: a diagram of its spectrum is necessary.

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COMPUTATIONAL SIMULATION OF MESOPIC VISION BASED ON CAMERA RECORDINGS

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ABSTRACT

Understanding mesopic vision is one of the hottest topics in lighting engineering [1]. The high importance of the field comes from the wide variety of the applications such as driving and other outdoor activities are performed in mesopic conditions at night. Therefore, it is extremely important to calculate the visibility of different objects in such conditions. In this paper, we present the algorithm and the first results of software, which is able to simulate the behaviour of human retina in scotopic, mesopic and photopic ranges, calculates the direction-dependent acuity. Our aim was to produce a practical tool to examine real-time situations. Therefore, classical camera recordings are used as input, which limits the accuracy but extends the range of applications.

Keywords: retina simulation, mesopic vision, nigh-time driving

1. INTRODUCTION

Our goal is to develop software, which is capable of simulating the properties of the visual sensation in real life situations without special hardware. This software ("*RetModel"*) can be used as a tool to investigate visual conditions in different lighting conditions i.e. during the night traffic situations. Our input is a movie file taken from a normal camera and our software displays it in the screen in a way that simulates the human visual perception via different circumstances.

In our model we considered and simulated the following features of human vision:

- Direction-dependent acuity: the photoreceptors on the human retina show significant variation in surface density and these cells are assembled into receptive fields. The density of these fields is defining the acuity of the retina in different regions.
- Different spectral sensitivity of cones and rods: simulating photopic, mesopic and scotopic ranges.

Direction dependent acuity is realized with two receptor-grids, one for the cones and the other for rods. The nodes of these two grids do not represent individual receptor cells, but a group of cells, which are connected in the layers of retina and produce one elementary "point" in our brain. The frames of the input movie are projected onto these grids and only the pixel values at the grid nodes are used in further calculations. Luminance and colour information is calculated in the nodes, and these values are interpolated for the whole field of view. For this reason the acuity will be lower in the area where the grid nodes has low density and vice versa.

A well-established simulation of mesopic vision can be found in [2]. In this work the authors use simulated image sequences in a large number of wavelength ranges that is they use detailed spectral data in each pixel. A problem with this method is that it is very difficult to collect detailed spectral data for each pixel in real situations.

A normal camera produces colour information in sRGB system, which can be translated into human cone signals L, M, S and also to photopic luminance (L_p). (Of course, these calculations assume a well calibrated camera.) Calculating scotopic intensity is much more problematic, because the commercial cameras are not intended to provide scotop-

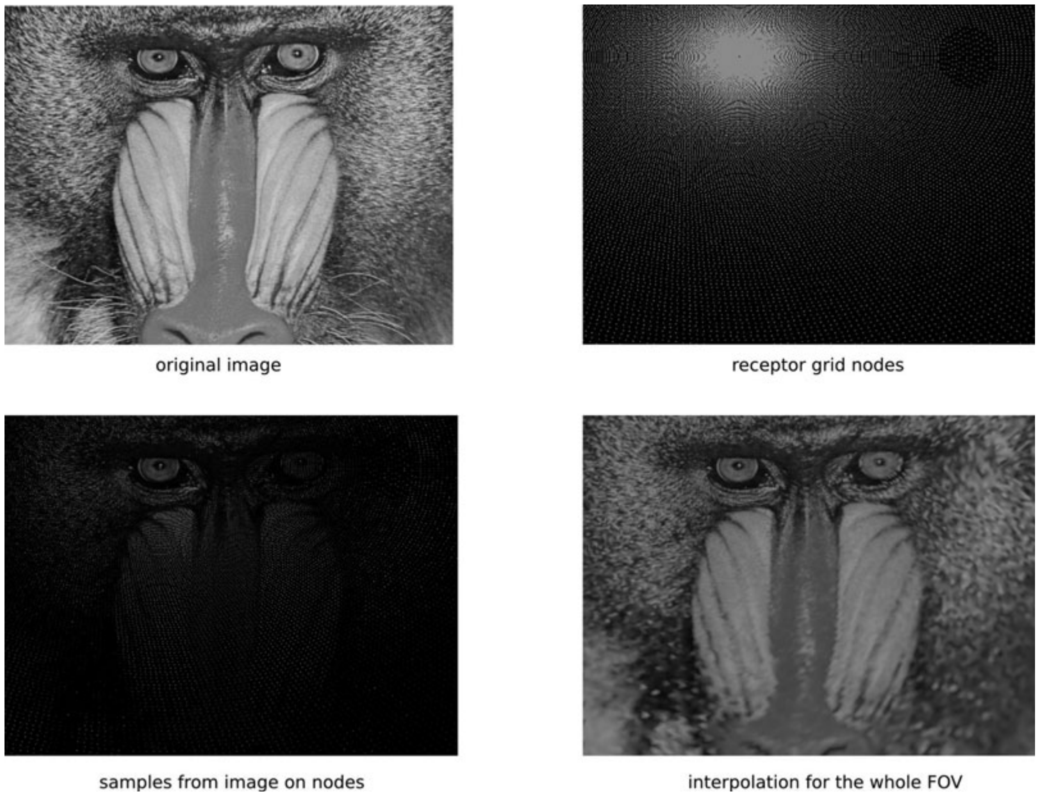


Fig. 1. Demonstration of sampling and interpolation steps with a sparse grid

ic vision data. However, with plausible assumptions about the type of the spectral distribution of the light sources, L_s/L_p ratio can be calculated approximately based on RGB values, therefore L_s can be calculated. Based on L_p and L_s, a mesopic L_m value can be calculated from a mesopic vision model, e.g. from the one of MOVE consortium [3]. Such way we will get a reasonable approximation of mesopic luminance based on a normal camera images. Detailed investigations showed that there are very special phenomena in the mesopic range, for example, non-additive terms in mesopic perception, [4]. In this work we can not take these effects into account, which limits the accuracy to the accuracy of [3].

It is important to note, that in our model we also implemented a chemical adaption mechanism in receptors, but due to the limited extent, it will be presented in a subsequent paper.

During the design and implementation of this software (called *RetModel*) our aim was to produce a real-time simulation. With well designed multi-threaded C++ code and using the features of graphic hardware (through OpenGL routines [5]) we were able achieve this aim.

In this paper, we present the method and test results of this code and show that it produces plausible results.

2. COMPUTATIONAL MODEL

2.1 Projection onto receptor grid

As a trade-off between accurate simulation of the retinal processes and practical usability, we use the following basic architecture of the computational model:

1. Define two grids of receptive fields for rods and cones respectively with spatially-variable density so that the acuity will be similar to direction-dependent acuity of human eye.
2. Project the input image (or series of input images) on these grids of rods and cones.
3. Calculate the modeled response of rods and cones.
4. Interpolate for the whole field of view.
5. Combine the signals of two grids based on luminance level.

For simplicity, we demonstrate this process at first on a still image in the photopic range in Fig. 1. The standard test image "baboon" was used as input.

We can see that the density of receptors is decreasing with eccentricity, therefore, we will have fewer samples in the peripheral areas, which results a loss in details there. In Fig. 1 the center of view is on the right eye of the baboon, therefore, it is com-

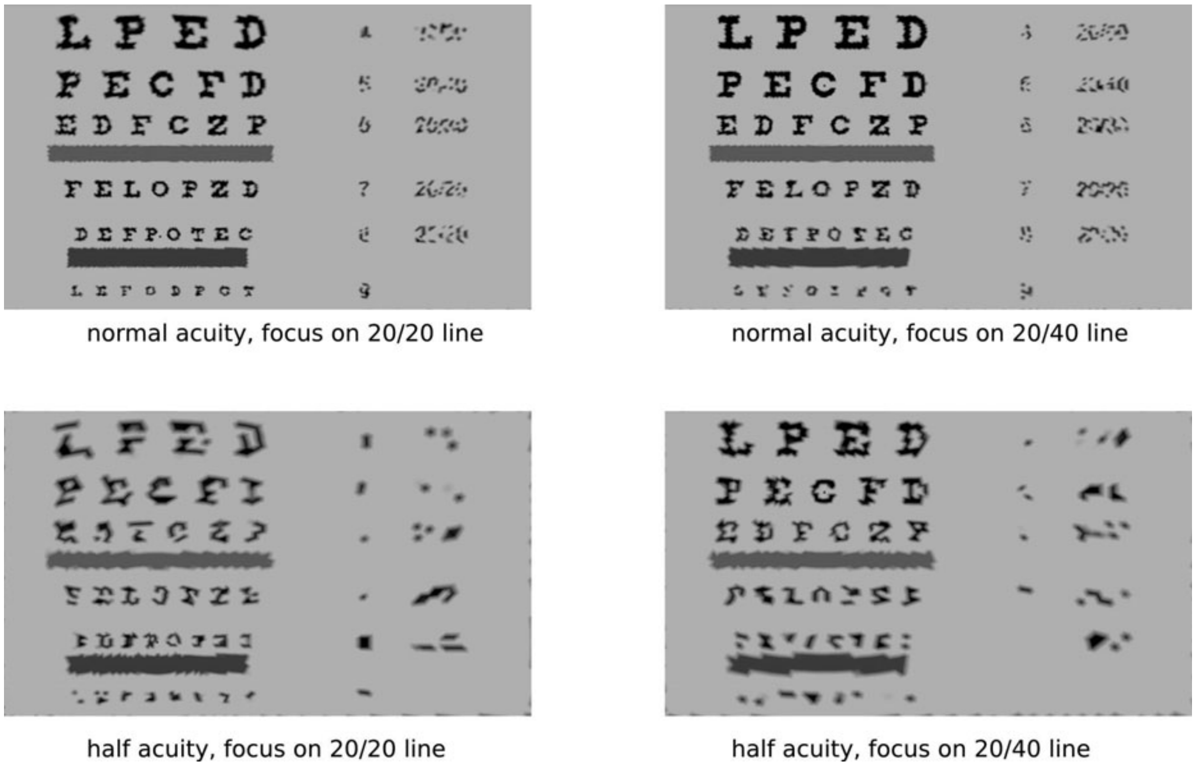


Fig. 2. Snellen test of *RetModel* in photopic conditions (Center of FOV is at tiny red square)

pletely sharp, the other eye is a little bit blurred, but the whiskers disappear completely. Note, that it is an artificially sparse grid for demonstration purposes. Since, with a real density of receptors the points on the upper right and lower left subfigs. would be too dense.

An input parameter of the retina simulation code is the resolution at the center of FOV with 60 lines/degree default value. We used the data from [6] to approximate the decrease of acuity as a function of eccentricity. Based on these data, we generate the grid of receptors (receptive fields) to reproduce the same resolution-dependence in a horizontal way. Vertically, a similar decay in acuity is assumed with 1.5 times less scale.

Similar acuity-dependence is simulated for rods based on [7].

The blind spot is also simulated. Two 4 degree-diameter areas are selected in horizontal direction at 12 degree eccentricity. In the case of single eye vision, we deleted all the receptors in the appropriate area. For two eye vision we reduce the number of them by a factor of two to simulate that even in two-eye case, the blind spot has negative effect on acuity.

After generating the receptors, we construct triangular meshes for rods and cones using Delaunay's method. Such triangular meshes can be rendered easily and quicly with OpenGL [5] using hardware acceleration. In our software, the grid of cones and rods are rendered independently with different transparent layers. This additive behavior is in accordance with the applied mesopic model [3].

In Fig. 2 we demonstrate that the acuity of our simulator is well calibrated to human vision. In the case of normal acuity the 20/20 line is clearly readable if the focus is on the line, but not readable in the case of the half resolution. Moreover, with a normal acuity if we focus on the 20/40 line, the 20/20 line will be blurred, but focusing on the 20/20 line, the letters are still readable from the 20/40 line.

The blurred parts in Fig. 2 look somehow artificial, but the results show that the simulation is realistic. In real life, the parts with low resolution at peripheral areas can not be “freeze in” and investigated with the same eye. But if we look at the normal acuity, subfigs. perpendicularly from an appropriate distance and focus on small red square representing the center of FOV, we will not recognise the blur of fig. in periphery, because that particular area in our eye has low resolution as well.

In Fig. 3 one can see the result of our code in a picture at a roundabout with complex traffic signs. In the picture *a)* the case of average resolution is shown, while in *b)* the vision of a half-acuity person is simulated. In both cases the center of FOV

a) normal acuity b) half acuity

Fig. 3. Looking at second traffic sign (from the left) with normal and half acuity vision

(tiny red square) is in the second (from left) sign. It is clear that an average person can read the letters of the right neighbour, but with half acuity. The driver has to fixate at every sign to read them, which is time consuming and can be a source of hazard.

2.2 Calculation of photopic and scotopic luminance

A movie file contains pixel values for each point for every frame. To turn them into physical luminance values is not a trivial task and can be done with moderate precision only after a detailed calibration process or in the belief of that the manufacturer did this calibration and the output images use a standard colour space, e.g. sRGB [8]. In our model, we assume the latter.

Using the standard sRGB functions we translate pixel *R, G, B* to linear R_l, G_l and B_l values (scaled into in 0,1 interval) and calculate Y as:

$Y=0.2126\,R_l + 0.7152\,G_l + 0.0722\,B_l$.

This Y has a linear connection with L_p photopic luminance, if we give the L_0 value that corresponds to Y=1 (brightest pixel), photopic value can be calculated as:

$$L_p=L_0\,Y=L_0\,(0.2126\,R_l + 0.7152\,G_l + 0.0722\,B_l). \qquad (1)$$

Finding a suitable approximation of scotopic luminance is more difficult. If our light source has $s\,(\lambda)$ spectrum and the surface has $\rho\,(\lambda)$ spectral reflectance, the ratio of scotopic and photopic luminance can be calculated as:

$$S/P = L_s/L_p = \frac{\int s(\lambda)\rho(\lambda)V'(\lambda)d\lambda}{\int s(\lambda)\rho(\lambda)V(\lambda)d\lambda}. \qquad (2)$$

(V and V' are the luminosity functions.)

Based on pixel values, we have R_l, G_l and B_l values, which can be calculated from spectral data using colour matching functions (CMFs) *r*, *g*, and *b*:

$$R_l = \int s(\lambda)\rho(\lambda)\bar{r}(\lambda)d\lambda; \qquad (3)$$

$$G_l = \int s(\lambda)\rho(\lambda)\bar{g}(\lambda)d\lambda; \qquad (4)$$

$$B_l = \int s(\lambda)\rho(\lambda)\bar{b}(\lambda)d\lambda. \qquad (5)$$

If we have only R_l, G_l and B_l, spectral data can not be reconstructed unequivocally: for a given $s\,(\lambda)$ spectrum and CMFs a large number of $\rho\,(\lambda)$ fulfills (3)– (5) requirements. However, these equations and $s\,(\lambda)\geq 0$ and $\rho\,(\lambda)\geq 0$ natural conditions do not allow for too big a variation in the *S/P* ratio. (Remember, we do not need spectra or a spectral reflectance function, we need only $L_s=L_p\,(S/P)$.)

This problem was considered in the following way. We used a set of $s\,(\lambda)$ spectra (standard illuminant A, D65, two fluorescent lamps, and a hypothetic source with equi-energy spectrum) and a parametric set of spectral reflectivity functions:

$$\rho = \rho(\lambda, p_1, p_2) \qquad (6)$$

This function was constructed from two Gaussian functions. In order to get all chromaticity coordinates, we had to change either the deviation or the center of the original functions:

$$r=R_l/(R_l+G_l+B_l) \text{ and } g=G_l/(R_l+G_l+B_l) \qquad (7)$$

To initialise our program the computer has to generate large interpolation tables for $r\,(p_1, p_2)$ and *g*

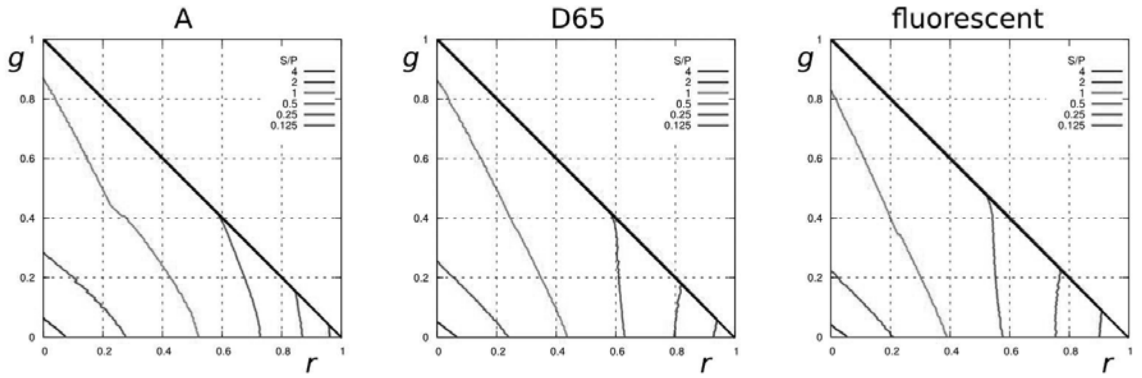


Fig. 4. *S/P* as a function of chromaticity coordinates with different light sources

(p_1, p_2) functions and the inverses: p_1 *(r, g)* and p_2 *(r, g)*. The next thing is to generate another interpolation table for *S/P* values as a function of *r* and *g* chromaticity coordinates based on the previous tables.

During the simulation, we calculate *r* and *g* using (7). We take (*S/P*) from the latter interpolation table. Using (1) we get L_p, and for the scotopic luminance we trivially get $L_s = L_p\ (S/P)$.

L_s and L_p is enough to determine the mesopic luminance from the MOVE model [3]:

$$L_m = \frac{m}{M(m)} L_p + \frac{(1-m)}{M(m)} L_s, \qquad (8)$$

where *M (m)* and the calculation process of *m* as a function of L_s and L_p can be fulfilled from [3].

While *M (m)* can be approximated with a simple function, we have to perform an iteration with arithmetic and logarithmic operators to get *m*. To speed up the process, we initialize a large interpolation table for $m\ (L_s, L_p)$ function for the scotopic and mesopic range. For photopic range $m=1$ holds.

An important question is: how is uncertain the *(S/P) (r, g)* function? We tested this question with 3 different sets (Gaussian, parabolic and piecewise constant) of parametric reflectance functions ($\rho\ (\lambda, p_1, p_2)$) and 5 different (A, D65, two fluorescent lamps, hypothetic equi-energy spectrum) light sources $s\ (\lambda)$. The results showed less than 20 % relative difference on averaging over *(r, g)* values. This small variation is credible, because for a given *(r, g)* value-pair we will get different $s\ (\lambda)$ and $\rho\ (\lambda, p_1, p_2)$, but their products have to be metameric, Fig. 4. Metamers spectra behavior is qualitatively similar. In long, medium and short wavelength-domains, they give the same L, M and S-cone signals. As the rod spectral sensitivity curve is between that of M and S cones, for relatively smooth functions rod signal and scotopic luminance must be similar for qualitatively acceptable spectra. Of course, one may construct special, artificial, strongly oscillating metamers with very different *(S/P)* values, but our calculations showed that for five realistic light sources with very dissimilar spectra and for three different sets of reflectivity functions the average variation is less than 20 %.

3. IMPLEMENTATION

The algorithm described above was implemented in C++ with multi-threading support and intensive usage of OpenGL routines. With multi-threading we could use all the CPU-cores for calculation, with OpenGL we could use the graphics hardware (GPU) for interpolation on receptor-grids, rendering layers of rods and cones, gamma-transformation in displaying. The free library "FFMPEG" is used for decoding video sequences.

The simulation code called "*RetModel*" can be complied in Windows and Linux systems. On an average workstation with 4 cores on Intel i5 or similar CPU with a recent GPU (with a good OpenGL driver) DVD-quality videos can be processed in real time.

RetModel tries to give back the visual experience in mesopic conditions. Therefore, we project the original RGB image onto the grid of cones and multiply the R, G and B values with *m/m (m)* to get the "photopic part" of the picture with colour vision. On the other hand, we calculate the scotopic luminosity L_s on the grid points of rods and give a little bit bluish gray colour to the points with intensity proportional to $(1-m)/M\ (m)\ L_s$. The bluish tone is somehow accidental, but it is in agreement with the subjective impression of night vision. The photopic and scotopic picture is superposed then. According to (8), for m=1 we get back the photopic, for m=0, we get back the scotopic cases, and between them their mixture. The combined picture is then multiplied by a normalisation factor (from user input), and inverse gamma-correction is applied to this combined picture before visualising it on the computer screen. A normalisation factor is needed, because *S/P* can be larger than 1, and it could result in overflow if L_p is near to L_0.

Instead of instant displaying this picture, our code can give back the map of L_m according to (8) in an array of floating point values.

4. TEST CALCULATIONS

For a simple test, a picture of a series of different colour discs was generated and simulated with different lighting conditions. More precisely, the L_0 value, which shows the luminance of brightest picture, was set to 100, 10, 1, 0.1 and 0.01. See Fig. 5 for results. The Purkinje's effect appears in this series clearly: in L_0=100 cd/ m^2 case every pixel is in photopic region, while for L_0=1 cd/ m^2 (high mesopic range) the red starts to fade away and we lose the colours in L_0=0.01 cd/ m^2 case. At this point the green and the blue disc will be brightest. Note that in the last case the resolution is smaller than that of in the first case, which demonstrates that the simulation program handles the different acuity in photopic and mesopic regions.

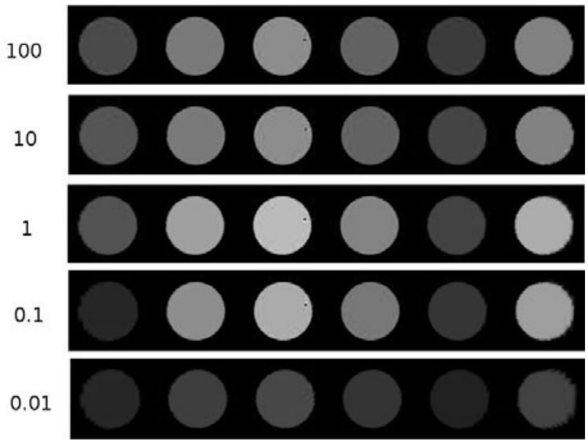
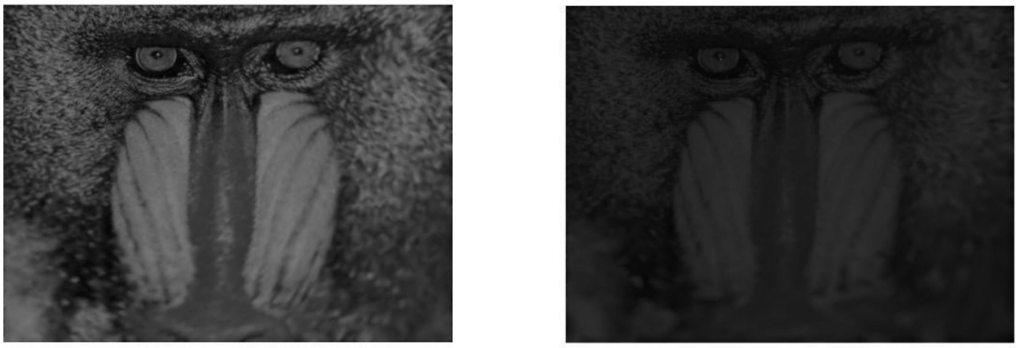


Fig. 5. Simulation of vision of a disc series with different L_0 [cd/ m^2] values

For another test, in Fig. 6 we present the results with standard test image "Baboon".

In Fig. 7 the result of the mesopic simulation in the case of a traffic situation is shown. It is based on a photo taken in cloudy weather conditions at daytime. Note that to get a more accurate simulation, we should take a closer look at the geometry of light sources, for example. Nevertheless, Fig. 7 shows that our code simulates Purkinje effect (see the red car and the green traffic signs) and the lower acuity in mesopic conditions, therefore, it is suitable for investigating visual conditions in such situations.



$L_0 = 1\mathrm{cd/m^2}$ $\qquad$ $L_0 = 0.01\mathrm{cd/m^2}$

Fig. 6. Baboon test image at high and low mesopic range

In this paper we can present only still images, but *RetModel* is capable for processing video files in real time on a modern workstation. Watching these simulations can be useful for an engineer responsible for designing lighting conditions in mesopic range.

5. CONCLUSIONS

We presented a method, which seems to be suitable for simulating mesopic vision based on normal camera image sequences. However, we have had to go on assumptions regarding to the light sources and the colour profile of the camera. Although the results are good, a moderate relative error ~ (20–30) % is as-

$L_0 = 1.0$

$L_0 = 0.1$

$L_0 = 0.01$

$L_0 = 0.001$

Fig. 7. Simulation of mesopic vision in a traffic situation for different L_0 values

sumable. The accuracy can be improved via camera calibration using detailed information about light sources used in the picture.

The simulation software (*RetModel*) can produce real time simulation on an average graphic workstation. Therefore, it seems to be a good tool for visual conditions in the mesopic range investigating, for example, at dawn or inside buildings, or at night traffic situations.

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DISCUSSION OF ENERGY EFFICIENCY EVALUATION

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ABSTRACT

A comparison is made of electric power consumed by various light sources of various luminous flux output. Based on simple calculations, a conclusion is made that an average luminous efficacy of the applied light sources for today in Russia, is unexpectedly high, because energy efficient lamps play a dominant role in luminous flux generation. Give this assumption, an evaluation is given of energy saving potential and hypothetical future trends of the electro-technical market.

Keywords: energy efficiency, illumination, consumed electric power, generated luminous flux, luminous efficacy, light sources, evolution prospectives

The system of artificial illumination is a major factor influencing all spheres of human activity. According to System Operator of the United Power System (SOUP) Open Society, power consumption in Russia amounted to 1016.3 billion kW·h in 2012. Approximately 13 % of this value, or about 130 billion kW·h was used for the illumination.

To understand the real potential for energy saving and most likely future trends of the Russian electrotechnical market development, in this article we have tried to evaluate how much electric power is consumed in Russia by various types of light sources and what luminous fluxes they generate.

With this aim, we have generalised indicators of the light source market size for the last three years (2010–2012) based on an analysis of industrial production volumes of Russian manufacturers and on information on import volume for this period. The data were kindly provided by the Russian Light Association. We also used materials of the Light Engineering Market journal [1].

Average values of main operational characteristics and lighting parameters of various lamp types were determined on the basis of [2], catalogue data of manufacturer companies, as well as on expert evaluations.

On average, one can evaluate the annual size of the Russian market of light sources for 2010–2012 as one billion units, of four lamp types which are mainly used for artificial illumination. These are:

1. Incandescent lamps (IL), including halogen – 600 million units a year.
2. Compact fluorescent lamps (CFL) – 130 million units a year.
3. Fluorescent lamps (FL) – 150 million units a year.
4. High pressure discharge lamps (HPML) – 15 million units a year.

Special purpose light sources (car, ship, etc.) amount to about 100 million units. They were not included in this research, because they are not really used for general illumination, and mostly consume electric power from alternative sources (storage batteries, generators et al).

Despite a rapid growth of the light-emitting diode market, we did not include this lamp type as a separate light source group in our research, because there are no statistics of their application for the selected period (2010 – 2012), and because their presence on the general illumination market is insufficient.

The total volume of the electric power consumed by each group of lamps per year (P_{Σ}), can be calculated using the following formula:

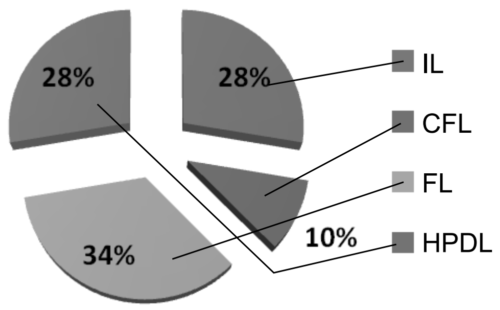

Fig. 1. Ratio of electric power consumed by various light sources annually

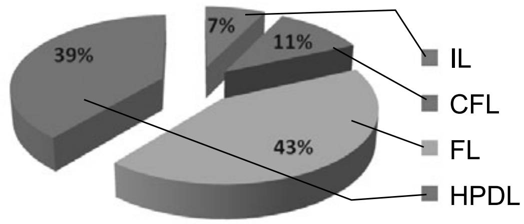

Fig. 2. Ratio of luminous flux generated by various light sources annually

$$P_\Sigma = Q \times P \times t, \quad (1)$$

where Q is number of lamps of this group, which were in operation during the investigated year (units), P is an average power consumption of a typical representative lamp of the group (W), t – operating duration of a typical representative lamp of the group a year (h).

Q is calculated using the formula:

$$Q = q \times \tau / t, \quad (2)$$

where q is an average annual capacity of this lamp group market (unit), τ is an average service life of a typical representative of the lamp group (h).

Substituting Q value from (2) to (1), we obtain:

$$P_\Sigma = q \times \tau \times P. \quad (3)$$

Thus the total volume of electric power consumed by each group of lamps, does not depend on the lamp number, which are in operation during the calculation year (Q), and on operating duration of a typical group representative per year (t).

Hence the luminous flux generated by the all lamps for each group (F_Σ), is calculated using the formula:

$$F_\Sigma = P_\Sigma \times H, \quad (4)$$

where H is an average luminous efficacy of a typical representative of the group, (lm/W).

The values of initial data used for the calculation, as well as P_Σ and F_Σ calculation results for each lamp type are given in Table 1, and P_Σ and F_Σ percentage ratios are in Fig. 1 and 2.

Now let us discuss the obtained results.

First, the total volume of the electric power consumed by the all types of lamps used for general illumination amounts to approximately 130 billion kW·h, which is consistent with the data given at the beginning of the article, and allows suggesting that the initial data used were correct.

Secondly, in the case of incandescent lamps, the P_Σ values expressed in percentage terms (28 %) and F_Σ (7 %), once again confirm the obvious fact that in the short term, this light source group provides the greatest potential for energy saving.

Thirdly, HPML group unexpectedly (at least for us) gives a high portion of the generated luminous flux (39 %), although this group only amounts to 1.5 % of the total quantity of manufactured lamps.

This is caused by a long service life of this lamp type and by their comparatively high single-unit power and provides evidence of the importance of this group of light sources on the Russian electro-technical market.

Fourthly, it is noticeable that energy efficient light sources (HPML, FL and CFL) at present play a dominant part in luminous flux generation in Russia. Their contribution in total amounts to 93 %. Average luminous efficacy of the used light sources is equal to 57 lm/W (Table 1), which is an unexpectedly high indicator.

When it comes to prospective future market development trends, it is undoubtable that in the first instance replacement of incandescent lamps with more effective lamps (CFL and light emitting diodes) will occur. Rapid replacement of CFLs with light emitting diodes is not so obvious. This group of lamps is most often seen in domestic use. The difference in energy efficiency here is not so considerable, and the price as a rule plays a critical role for buyers.

The trend to gradual replacement of the fluorescent lamp group with light emitting diodes is important, because light emitting diodes have the best

Table 1. Total volume of the consumed electric power and total generated luminous flux of the group per year

Lamp type	Average annual capacity of the market in 2010–2012, million units	Averaged power of a typical representative of the group, W	Average luminous efficacy of a typical representative of the group, lm/W	Average service life of a typical representative, h	Total volume of electric power consumed by a group of lamps per year, kW·h	Total luminous flux generated by the group of lamps per year, billion klm·h
IL	600	60	15	1000	36	540
CFL	130	13	60	8000	13	810
FL	150	30	70	10000	45	3150
HPML	15	200	80	12000	36	2880
TOTAL					130	7380

operational parameters with a relatively low power consumption.

The HPML group shows the highest indicators of energy efficiency with a relatively low price, and hence it has the most stable position at the market. Within the HPML group one can also predict an increase in more effective sodium and metal halogen lamps portion owing to MAL replacement. Later on, replacement of gas-discharge light sources with light emitting diodes will occur as long as the characteristics of the latter improve and their cost decreases.

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RAINBOW ELECTRONICS: FORMATION OF A CIVILIZED MARKET OF LIGHT EMITTING DIODE ILLUMINATION

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ABSTRACT

The luminaire structures with light emitting diodes developed recently by *Rainbow Electronics* Company allowed the company to create a powerful package of design proposals for office, housing, services and utilities, street, industrial and furniture luminaires. The broad range of design solutions allows lighting companies to fully utilize the engineering potential of *Rainbow Electronics* to solve their problems.

The article considers different aspects of designing luminaires with high power light-emitting diode light sources and secondary optics.

Keywords: light source, light emitting diode, *CREE*, light-emitting diode module, illumination using light emitting diodes (LEDIL), luminaire with light emitting diodes, secondary optics, *LEDiL*

There are different points of view for the rationality of using light emitting diode illumination (LEDIL) in the context of the wide availability of luminaires with traditional light sources (LS). Many lighting specialists criticise LEDIL proponents for importunate and persuasive PR communication and businessmen “from a garage” – for low levels of competence in materials technology, heat engineering and lighting calculation problems. In the overwhelming majority of cases, this attitude is not a result of a shortage of specialist knowledge. It is the result of a misconception LEDIL’s specific characteristics and a unprofessional approach to LEDIL introduction in Russia.

Nevertheless, some commentators, seriously or in jest, envisage an economic development model for Russia’s energy saving as “modernisation, innovations and as their crown, light-emitting diode bulbs”.

A fixation on LEDIL importance in the consciousness of the masses has really taken place, and there are objective preconditions for this. LEDILs provide the possibility of flexible luminous flux control, and long time between failures in the context of continuous growth of electric power tariffs and very strict limitations of energy the load for new construction in some regions of the country. All of this leaves little choice but the LEDIL.

For example, the Moscow Business Centre constructed within the Third transport ring (TTR), within strict limits for the connected energy load, must reject installing server equipment, or switch its workers to work at the daytime only. Neither of these is an acceptable option for business. The only remaining option is to introduce energy saving illumination technologies.

And what are these technologies? Could they be illumination using compact FLs? Sometimes, yes, but more often, this are correctly designed and professionally integrated LEDIL.

The physiological and medical aspects of this approach are beyond the scope of this article. However, a wide field for speculative evaluations exists, and in many cases there is no LEDIL alternative. Looking for a party to develop the devices and implement projects, Russia might look towards the Chinese manufacturers of light-emitting diode LSs. Howev-

Fig. 1

er, in an overwhelming majority of cases, these show a weak engineering analysis of their products and demonstrate high risks of faults in serial production goods. Expensive logistics and long delivery times, unacceptable for many projects, make this source of products unpalatable in Russia.

Turning to homegrown inventors "from their garages", they have a good grasp of electronics at best, but are fuelled by a natural desire of obtaining an acceptable rate of return as soon as possible. This means their technical solutions are unlikely to be of good quality and reliability.

Considering large-scale lighting companies, which manufacture luminaires using traditional LSs, may seem the optimal option. These market players have an understanding lighting products, strong views about market development trends and evidence of real market evaluations, a firm production and technological base, up and running distribution networks. However, many are at an initial stage of mastering the light-emitting diode technologies, and they do not have enough understanding of the peculiar properties of light-emitting diode LS choice, most suitable design and competitive commercial evaluation of a luminaire and of the targeted marketing efforts needed to promote the new product to the market.

Both large-scale lighting enterprises, and small companies need a partner experienced in implementing the preset technical and economic requirements to a luminaire using calculations, drawings and engineering models for high-quality luminaire design, with the commercial success of the product in mind.

For the last four years *Rainbow Electronics* has been such a partner; the lighting division implements a business model named "*distribution-by-design*".

1. About *Rainbow Electronics* Company

With origins in light-emitting diode (American *CREE*) products distribution, four years ago, *Rainbow Electronics* Company (Fig. 1) has expanded to suggesting ready technical solutions to its clients based on these products.

In 2010, a street luminaire for class B road illumination, the first in the "luminaire of the year" project, was presented to the general public. In 2011 the company presented an industrial luminaire of *High-Bay* class, optimised for suspension at a height of 12 m. A patent was obtained for its structure.

In 2012 *CREE* named *Rainbow Electronics* as its solution supplier partner for this and other achievements of the company in designing luminaires, and gave it the title of *CSP* (*CREE Solution Provider*).

In the same year, the company joined the NP LEDM (Noncommercial partnership of light emitting diode manufacturers and systems based on LEDs). This noncommercial partnership was a unique entity where Russian manufacturers of light emitting diodes and luminaires could lobby their needs within the regulatory system and voluntary branch regulation. *Rainbow Electronics,* whilst not a manufacturer of luminaires, takes part in the analysis of regulations and makes its own recommendations.

An altogether different project, "luminaire of the year", was implemented in 2012. It was a track luminaire for accent illumination. The luminaire was developed and created as an alternative to a 70 W MHL luminaire for application in commercial and sales spaces. Special technical solutions contributed to the luminaire's success. It featured a specially developed optical system with variable focal length and unique casing design created by the Artemy Lebedev's studio. As a result, the luminaire was launched in the high-end segment of LEDiL Company stores, where Italian and German lighting brands dominated. More detail about the development stages and solutions applied when designing this luminaire are given in section 3 of this article.

In 2013 R*ainbow Electronics* became the first company in Europe to obtain the status of manufacturer partner of secondary optics to *LEDiL* Company. The *LOSP* status, (*LEDiL Optics Solution Provider*), was obtained due to some projects undertaken together with *LEDiL*. These were connected with development, manufacturing and introduction of secondary optics ideally suited for various lighting problems.

A designer, an optical scientist, a heat engineer, electronics engineers and light engineers are the highly professional members of the lighting division of *Rainbow Electronics* Company. This is the team delivering technically appropriate solutions to client problems.

The commercial department analyses the market situation and competitive standing of the products developed on the market, controls all shipments and warranties.

The company has a presence in Moscow, St. Petersburg, Minsk, Kiev, Novosibirsk and Ekaterinburg. In each of these cities, there is an interaction between the regional offices of *Rainbow Electronics* and the Engineering department of the Lighting division.

The company has its own production capacities for the assembly of luminaire components: light-emitting diode modules, power supplies, controllers – in Novopolotsk (Belarus) and in Kiev (Ukrain).

For its luminaires with light emitting diodes, *Rainbow Electronics* uses the following components: *CREE* light emitting diodes; *LEDiL* secondary optics; power units from IRBIS, *LG Innotek* and *Moons*; modules and systems of active cooling from *SUNON*; illumination control ready modules from *LG Innotek* and of its own production.

The company's quality management system is certified in accordance with the standard GOST R ISO 9001–2008.

2. Our developments

Currently, *Rainbow Electronics* has selected several popular applications of light emitting diode (luminaire groups), for each of which light-emitting diode modules (LEDM) types are already developed and manufactured.

Luminaires for housing and public utilities and indoor illumination of small sites and rooms

The following properties are most demanded for this consumer group of luminaires: equivalence by luminous flux to incandescent lamps of correspondent power; power consumption of 8–10 W with a luminous flux of 800–1000 lm; a high uniformity of light distribution; little or no blinding effect; correlated colour temperature T_c of approximately 5500 K; vandalism protection; service-free; a long service life and low cost. Some characteristics of these *Rainbow Electronics* production LEDMs is given in Table 1, and others are as fol-

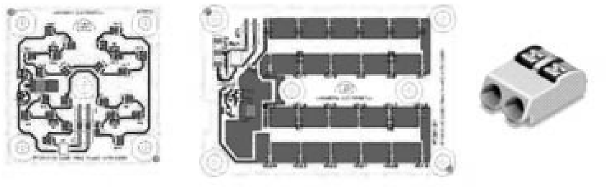

Fig. 2

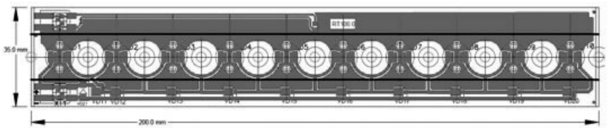

Fig. 3

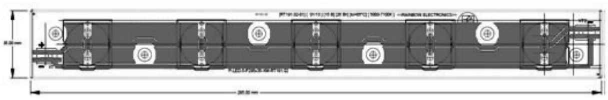

Fig. 4

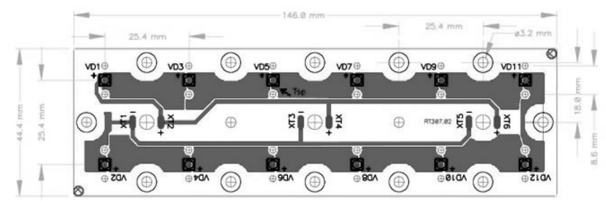

Fig. 5

lows: mains voltage is 220 V; power factor ≤ 0.93; light ripple factor ≤ 50 %; T_c = 4700–6000 K; general colour rendering index R_a > 70; Metal Core Printed Circuit Board *(MCPCB)* of 1.0 mm thickness; the slot is on the board; service life is in accordance with the *LM80* standard (> 50 thousand h). LEDMs assembled to order are supplied without slots, and light emitting diodes of T_c = 3000, 4000 and 4500 K are available for installation.

Armstrong luminaires for office spaces and corridors

The following features are required from these luminaires: luminous flux equivalent to four FLs of 18 W power; power consumption no greater than 40 or 30 W with luminous flux 3600 or 2500 lm (corridors) respectively; highly uniform light distribution; little or no blinding effect; T_c = 4500, 5000 and 4000 K (with an accuracy of ± 200 K); power unit with power factor correction ensuring a low starting current; light ripple factor < 5 %; convenience and adaptability to assembling LEDM inside a luminaire; a long service life and a low cost.

Some characteristics of these LEDMs of *Rainbow Electronics* production are given in Table 2, and others include: R_a = 80–85; self-holding slot for the

Table 1. LEDMs for housing and public utilities of *Rainbow Electronics* production (The prices are given so that the manufacturers could evaluate specific cost of the components in the structure of the luminaire prime cost)

Short LEDM codes	Number of light emitting diodes, pieces	Luminous flux, lm *	Power consumption, W	Board size, mm	Wholesale price, $
RT295.03–01 (Fig. 2)	20	830	10	70×70	6.8
RT295.03–02	24	930	8.5	70×70	7.5
RT295.03–03	24	1060	10	70×70	7.5
RT301.03–01	20	830	10	115 ×75	7.4
RT301.03–02	24	930	8.5	115×75	8.1
RT301.03–03	24	1060	10	115×75	8.1

* Operation mode at the temperature T_{sp} = 50 °C in the soldering point of a light emitting diode.

Table 2. LEDMs for office illumination of *Rainbow Electronics* production

Short LEDM codes	LED number, pieces	T_c, K	Luminous flux at a current of 350 mA, lm *	Power consumption at a current of 350 mA, W **	Board material	Whole sale price, $, starting from
RT371.01–01	16	5000	1160	8.75	AL MCPCB	3.75
RT371.01–02	16	4500	1100	8.75	AL MCPCB	3.75
RT349.01–01	12	5000	870	6.6	FR4	3.18
RT349.01–02	12	4500	820	6.6	FR4	3.18

* Operation mode at T_{sp} = 40 °C
** Operation mode ignoring power unit efficiency

wire; light emitting diodes of T_c = 3000, 3500 and 4000 K can be installed; power supply unit parameters are 40 W, 350 mA, *IP66*, efficiency > 90 %.

Most often four LEDMs connected in series are used in the luminaire. The number of LEDM can be changed by means of commutation changing.

The proposed form-factor is a narrow long board with light emitting diodes of no more than 1 W power, which are suitable as industrial luminaires for low suspension and a wide light distribution, for commercial equipment luminaires and for indoor illumination luminaires.

If there is no existing circuit board of the required dimensions or with the required location and number of light emitting diodes, specialists at *Rainbow Electronics* will develop a new version of the printed-circuit board. The minimum completion period for this work is 24 hours.

Luminaires for indoor and external illumination of industrial sites and warehouses, for illumination of streets, parks and tunnels

The main requirements of luminaires in these fields of application are as follows: a special light distribution; a high degree of shell protection (*IP*); high luminous efficacy of 80–120 lm/W; acceptable mass-dimensional parameters and controllability.

Universal printed-circuit boards are developed for this wide range of applications. They are designed for use with different secondary optics, which form the necessary light distribution. Using different combinations of secondary optics, number of boards, power units and cases, the customer obtains several versions of LEDMs for these luminaires with a high degree of unification (Tables 3–7).

In order for the luminaires to take their finished form, *Rainbow Electronics'* product range includes

Fig. 6

Fig. 7

elements of radiator cases and ready cases, as well as selected power units. These elements are designed specifically LEDMs listed, taking into account thermal modes and optical characteristics.

For luminaire manufacturer companies, which are not ready to invest in the development, *Rainbow Electronics* proposes a site assembly of ready luminaire components for different purposes: industrial (Figs. 6 and 7), street (Fig. 8), office, etc. In order to implement this, *Rainbow Electronics* has created some typical solutions and invested its own funds into cases and heat removal systems. Several implementations of each series of luminaires are analysed against a wide range of customer requirements. The technical data, solution cost, and project implementation periods are considered as the major parameters.

To enable fast delivery, there is a warehouse reserve of ready boards with and without mounted light emitting diodes, accompanying power units, secondary optics units and other components for typical illumination devices and solutions.

Fig. 8

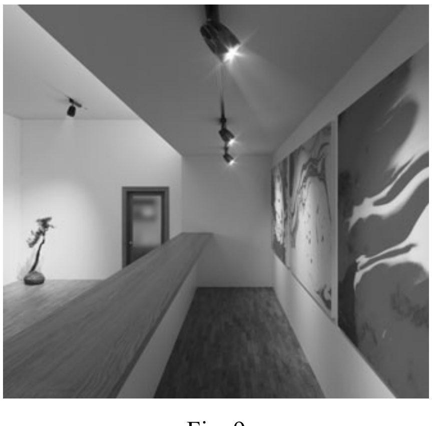

Fig. 9

3. Stages of luminaire development

The design abilities and lighting product calculation parameters of *Rainbow Electronics* are most clearly demonstrated by the development process of an one of the company's interesting products – an accent luminaire with light emitting diodes for illumination of commercial spaces.

The idea of developing this product was generated by the *Interlight* 2011 exhibition, which showed that there was an absence of adequate solutions from manufacturers of light-emitting diodes for this type of luminaire. The needs of the commercial illumination market were unsatisfied. Track luminaires with MHLs of 70 W power were the most widespread in this market sector. Engineers of *Rainbow Electronics* enthusiastically embarked on a design of this unique product, which could fill a market gap. Just one year later, at *Interlight* 2012, the company presented an operational model of the luminaire, which embodied advanced achievements in the LEDIL field (Fig. 9).

This luminaire is intended to generate areas of raised illuminance in order to attract visitors' attention to exposition stands in a store. Therefore, this application implied increased requirements for energy efficiency, and light quality. Here the "quality" includes such parameters as R_a and standard deviation of colour matching (*SDCM*). One more requirement is the availability of two radiation angles (20° and 40°) of the luminaire and certainly, its appearance: the product should be modern and not

Table 3. Light-emitting diode module of *RT100* series with the slot on the board and with openings for installing a single optics of *LEDiL* production

Short LEDM code	Light emitting diode	Size, mm	T_c, K	Luminous flux, lm /at a current, mA*	Power consumption, W*	Wholesale price, $
RT100.01–04 (Fig. 3)	*XTE* (10 pieces)	200×35	4750	2656/700 3470/1000	22.3 33.2	17.4

* At crystal temperature T_j = 25 °C.

Table 4. Light-emitting diode modules of *RT191* series with a slot on the board and with openings for installing a single optics of *LEDiL* production

Short LEDM code	Light emitting diode	Size, mm	T_c, K	Luminous flux, lm/at a current, mA*	Power consumption, W *	Wholesale price, $
RT191.02–02	XMLB (5 pieces)	295×35	5000	2500/ 140 2990/ 1750	21.8 27.9	21
RT191.02–03 (Fig. 4)				2700/ 1400 3230/ 1750	21.8 27.9	22.4

At crystal temperature T_j = 25 °C.

Table 5. Light-emitting diode modules of *RT355 – RT358* series

(They are designed for using *STRADA-2×2 s*eries group secondary optics of *LEDiL* production. This optics allows producing luminaires for high and low suspensions, street luminaires and searchlights)

Short LEDM code	Light emitting diode	Size, mm	T_c, K	Luminous flux, lm /at a current, mA*	Power consumption, W*	Whole sale price, $
RT355.01–01	*XTE* (24 pieces)	180×120	4700	4850/ 500 8330/ 1000	37.1 80	35.6
RT357.01–01	*XTE* (40 pieces)	267×167	4700	10620/ 700 13880/ 1000	89.6 133	59.6
RT356.01–01	*XBD* (24 pieces)	180×120	5000	4170/ 500 5360/ 700	37.6 54.4	26.5
RT358.01–01	*XBD* (40 pieces)	267×167	5000	6950/ 500 8940/ 700	62.7 90.6	44.4

* At crystal temperature T_j = 25 °C

distract visitor attention from the exposition stands, it should be simple for mounting and convenient for control. The list of requirements for this luminaire is given in Table 8.

An investigation revealed that no such luminaires with light emitting diodes were available in serial production at similar technical parameters. This implied that their design and production are very complex.

Creating a new illumination device includes selecting and developing many hardware components. For illustration purposes, we will consider the main ones stage by stage: selection of an optimum light source by its characteristics, implementation of the

Table 6. Light-emitting diode module of RT173 series
(It is designed for using 5×1 secondary optics of *LEDiL* production. This optics allows producing luminaires for suspension height of 12 m, street luminaires and searchlights.)

Short LEDM code	Light emitting diode	Size, mm	T_c, K	Luminous flux, lm/at a current, mA*	Power consumption, W*	Wholesale price, $
RT173.02–03	XML (5 pieces)	118×20	4700	2910/ 1400 3480/ 1750	21.8 27.9	17

* At crystal temperature T_j = 25 °C

Table 7. Light-emitting diode modules of *RT307* and *RT308* series
(They allow using group secondary optics of *STRADA-12×1* series of *LEDiL* production. This is optimal for street and motor road luminaires)

Short LEDM code	Light emitting diode	Size, mm	T_c, K	Luminous flux, lm/at a current, mA*	Power consumption, W*	Wholesale price, $
RT307.02–01 (Fig. 5)	XTE (12 pieces)	146× 44	4700	3187/ 700 4165/ 1000	26.8 39.9	16.6
RT308.02–01	XBD (12 pieces)			2680/ 700	27.2	12.5

* At crystal temperature T_j = 25 °C

Table 8. Requirements of an accent luminaire with light emitting diodes for commercial spaces

Luminaire dimensions	Diameter ≤ 130 mm, height ≤ 300 mm	
Mass of the luminaire, kg	~ 2.0	
Colour	Metallic, black or white (matte colour)	
Configuration	Flowed round or roundish	
Freedom degree number	Two: 0–360° and 0–90°	
Fastening	To a standard bas duct	
Power unit protection	Against voltage jumps	
Radiation angle	Adjustable (20 and 40°)	
Efficiency, %	> 80	
R_a	90+	80+
T_c, K	3000	3000 4000
Luminous flux, lm	~ 4400	> 5000
Luminous efficacy, lm/W	> 55	
Power, W	< 80	
Service life, hr	> 50000	
Mains voltage, V	220–240 (50–60 Hz)	

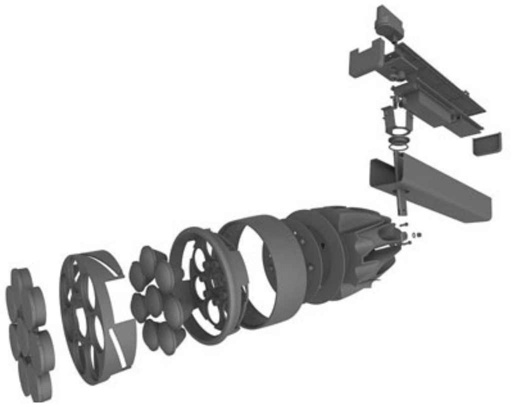

Fig. 10

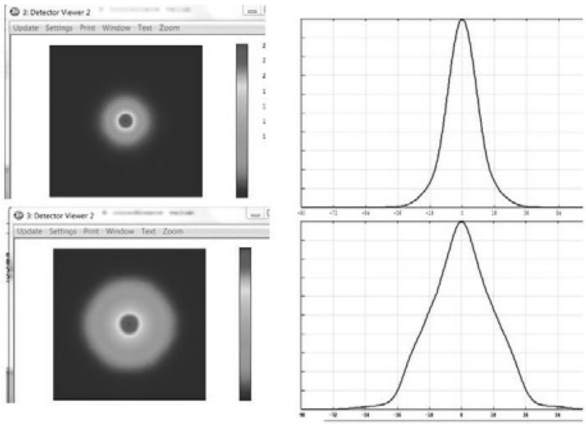

Fig. 11

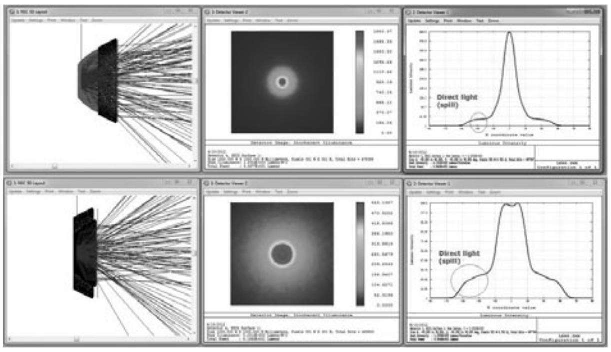

Fig. 12

optical system, design development and thermal simulation of the resulting structure.

Stage 1. The light emitting diode as a LS should primarily meet the following requirements: T_c = 3000–4000 K and $R_a \geq 90$ (the latter is especially important in commercial illumination).

This brings us to the most frequent problem: when luminous flux requirements conflict with mass and dimension limitations of the luminaire.

This discrepancy led to a failure at the start of the luminaire structure development. The number of *XLamp MT-G* light emitting diodes (*CREE*) with the necessary characteristics, was found to be twelve. This meant that it was impossible to stay within the maximum dimension parameters of the luminaire (cross section diameter of the case is no more than 130 mm). At this same time, we were amongst the first in Russia to learn that *CREE* was preparing new light emitting diodes (*XLamp MT-G2* with a raised luminous efficacy) for manufacture. With these new models, the number of light emitting diodes could be decreased to eight, and the case cross section size – to 120 mm!

Stage 2. Within the well-established practice of commercial spaces, two types of axisymmetric light distribution are most widespread: with radiation angles of 20° and 40°. Therefore, the best known European brands provide a set of two types of reflectors as accessories for their products. The problem faced by store managers is the need for additional storage space for the replaceable parts and specially trained personnel to replace the reflectors in the luminaire. To address this problem, and to improve LD serviceability, it was necessary to enable the users to change the radiation angle quickly and easily. A composed optical system was used, consisting of two elements, which could move relative to each other (Fig. 10).

Specialists at *Rainbow Electronics* have developed their own structure for a composed holder, which ensures fastening the optical elements, their smooth movement relative to each other and reliable fixing at two end positions providing radiation angles of 20 and 40 °. A simple turn of the external ring allows changing the radiation angle without additional work. Engineers of *Rainbow Electronics* worked out in advance the mechanisms of this system, established the working capacity of the whole mechanism using a model, and then formulated (as a design document) case manufacture task for the composed optical system.

Such systems can be constructed using both reflectors and lenses. However, reflectors cannot ensure the necessary quality of light distribution within the specified dimensions, as can be seen from Fig. 11. Areas with intolerable levels of luminous intensity appear which leads to decreased luminance contrast on the illuminated surface. There are no such disadvantages in the lens system designed and manufactured by specialists from Finnish *LEDiL* Company especially for *RainbowElectronics* (Fig. 12).

Table 9. Comparison of the accent luminaire with light emitting diodes for illumination of commercial spaces (a model), developed by *Rainbow Electronics,* with its MHL analogs

Compared luminaires	Power, W	Luminous flux, lm	Luminous efficacy, lm/W	Radiation angle, degree
Our luminaire (R_a = 90, T_c = 3000 K	75	4760	63	18–20
Analogue "MHL 1"	80	4158	52	17
Analogue "MHL 2"	80	4554	57	16

Fig. 13

Stage 3. Artemy Lebedev's design studio, a leading design company was involved in the development of the exterior design of the luminaire. The studio provided a large number of rough plans, of which the most suitable were selected, and a joint effort development process began.

The case not only needed to be aesthetically attractive, but also meet several technological and structural requirements: effective heat removal from the light emitting diodes due to radiator geometry, configuration, etc. Fig. 13 shows the evolution of appearance of the case as a radiator of the luminaire.

Stage 4. Engineers of *Rainbow Electronics* faced a very complex challenge: to ensure effective heat removal from the light emitting diodes within the limited dimension and mass parameters specified by the technical requirements. Using special purpose software, thermal simulations were carried out to model the luminaire's thermal operation mode in order to avoid the overheating of its components. The thermal calculation can determine the temperature of every element of the luminaire with a high degree of accuracy, which helps to avoid errors at the design stage, and ultimately to determine the structure and save considerable time and funds when product modelling.

Fig. 14

Modelling the ready product fully confirmed the calculated characteristics from the thermal simulations. The parameters of outcome luminaire product (Fig. 14) surpass its analogue based on an MHL of 70 W power (Table 9). It can be controlled under *DALI* or 0–10 V protocols, which makes the luminaire to even more energy-efficient.

In conclusion, **we would like to** answer the question of why *Rainbow Electronics* goes into such detail to describe its conceptual approaches to luminaire design with light emitting diodes in articles or at seminars, trainings and exhibitions? After all, back-alley manufacturers in pursuit of profit, can blindly copy the successful structural and technical solutions of *Rainbow Electronics,* violating copyrights.

We consider that the practice of training itself compels luminaire manufacturers to evaluate the quality of their products critically and responsibly, to see their sensible approaches and to minimize their own design costs. It is pleasant to realise that the contribution of *Rainbow Electronics* to the development of the lighting branch leads to a gradual growth in the number of more civilized manufacturers and to a constant growth of their market "weight". As a matter of fact, with growing well-being and general culture in the country, the growing stability of the lighting business is to a large extent a fruit of its moral and reputational capital, which is getting stronger.

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LIGHT ENGINEERING AND COMMERCIALISATION OF TECHNOLOGIES

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ABSTRACT

Basic provisions for technology commercialisation when developing lighting products are considered. The specific characteristics terms and definitions of developing the photometric instruments forming the basis of many scientific light and engineering researches are explained. A detailed description of the theoretical basis of technology commercialisation with practical examples and recommendations is given in monograph [1]. This article proposes a review of past and present theory and practice of commercialisation work at leading manufacturers within the light and engineering field.

Keywords: light and engineering, technology, innovation, investments, efficiency, commercialisation, marketing, measuring instruments, research and development (R and D), economics, market, company, university, standards

Currently, there is an innovative model of economic development applied in many sectors for the Russian economy. Its purpose is to raise the quality and competitiveness of domestic products, as well as promote the products on world markets. As a result, questions of science, production and business coordination become critical points of discussion. During commercialisation, the interaction of these spheres occurs. Research and development interacts with the concepts such marketing and management, which have fully entered the lighting sector and continue to be assimilated due to their impacts on efficiency and profitability.

Features of technology commercialisation in light engineering

Light engineering is an applied science, the development directions of which are determined largely by macroeconomic processes. In today's Russia, extremely low electricity costs, compared to European countries, has created a favourable context for widespread application of inefficient lighting solutions based on incandescent lamps (IL) and fluorescent lamps (FL) with primitive luminaires, which have low utilization coefficients of luminous flux, with very limited use of energy saving technologies. Research into population health has a significant influence on the development of illumination systems. Changes in illumination control systems, reducing radiation ripple level and the UV portion of light are all measures aimed at increasing people safety at work and at rest. As illumination equipment innovations are introduced, the photometric device market is growing in parallel to provide required measurements at a necessary level of accuracy. Elements of market relations gradually start to work when producing, operating and measuring optical radiation. Competition increases not only between individual manufacturers of lighting products, but also between groups. It would seem that FL manufactures who have strongly occupied the market, are opposed by the rising light-emitting diode manufacturers. By using state-of-the-art radiation and image measuring instruments, cinemas can improve the quality of their projections, gaining competitive advantage improving profit. Producers of shows with new lighting effect, innovative lighting systems, and complex image facilities, can raise interest in the performance, attracting new audiences. Even on the consumer product market, colour control is commercially important: dietician researchers in the USA found out that if a meal on the plate has different colours, people unconsciously try to eat as much as possible, because bright dishes seem to have greater taste variety.

Innovative activity and innovative modes

The strategy for innovative development and the choice of the mode of innovation should be formed based on the analysis of the market situation and of the state of the company. Companies, which have a strong market position, are likely to use an investment model named the "market draft". Essentially, this model asks the question: "How can a topical business problem be solved through the company's technological development?"

However, when companies are driven primarily by scientific and technical interests, they can obtain knowledge and generate technical solutions without a prior understanding of the market. This innovation model is called a "technological push" or "technological pressure". This model asks the question: "Which goods and services with market demand can be developed with the new solutions?"

The urgency of the technology commercialisation became especially evident in the 1980 s. The USSR, with its powerful academia, began to lag behind the first world countries in the development and manufacture of new types of technical facilities (probably with the exception of military R&D). Not so long ago a quarter of the world's planes were produced in the USSR; today, for Russian, this is less than one percent. Initially, Russia began lag behind the USA, then fell behind other countries (China, India and the EU) in the development of the space program. The lag in car industry development, electronic goods and systems manufacture, and in others parts of industry were significant noticeable also. This was especially noticeable for modern home appliance production, despite clumsy government attempts to make the strongest defensive structures produce consumer goods (CG). These enterprises received a state order to manufacture a certain range of CG products, which according to the State Planning Committee of the USSR, would meet all the needs of the domestic population. The analysis of this demand was based on a clearly inefficient planning system, which did not take account of all of the data. But politicians did not see the planning and forecasting system as flawed, rather blamed an ignorance of appropriate parameters and strong forecasting methodologies.

Certainly, there were many experts who proposed cautious transition to a market economy, which would allow a real evaluation of demand and mobilise consumption of goods or services. However, this was contrary to the concepts of the Party and the role of the authorities in the distribution of goods. Soon, many examples of effective R&D appeared throughout the world. These were known and reported in detail. It was these publications, which became classics of the marketing, management, and control systems literature.

Today, there are four main approaches to technology commercialisation, which are considered as standard methods for increasing economic efficiency.

– Research and development commissioned by production companies

In this case, scientists and/or scientific teams generate additional income; sell their competence and knowledge, transforming them into a consumer-oriented group, solving the problems arising from niche scientific production attempts. At the moment, this method of commercialisation is underdeveloped in Russia. There is a critical shortage in companies' ability to bring universities and scientific institutes to the table to hold develop solutions. An interesting configuration of interaction has developed between Optogan company and the S-P University of Information Technology Scientific-and-Research Organisation. They announced an admission of bachelors and licentiates to the basic master program under the Chair of "Light-emitting diode technologies". The students who began training in September 2013, have the opportunity to acquire professional training, which is in high demand on the market by small and middle sized technology companies. Another example is the cooperation between Svetlana-optoelectronics Joint-Stock Company and TKA Scientific and Technical Enterprise (STE) Open Company. Over several years, TKA STE developed and produced a series of new instruments for measuring key parameters of light emitting diodes, commissioned by Svetlana-optoelectronics. As a result, Svetlana-optoelectronics completely equipped its laboratories with the necessary measuring equipment, and TKA STE commercialised its manufacturing process, starting serial production of devices for the measurement of flux and spectrum of light emitting diodes. One more example is the team effort of Optogan Company, of Organic Light Solutions and of the Skolkovo Innovative Centre, where an innovative technology for radiation sources production is being developed based on organic light emitting diodes with an intelligent control system for radiation flux and chromaticity.

– ***Carrying out new scientific research*** financed by state or international programmes or funds in high priority fields. The distinguishing feature of these projects is the "customer" of the research effort; not a specific manufacturer but the state, which is expecting to get certain benefits from the research. These can be attaining leading world positions in the scientific field and achieving competitive priorities for the national economy. As in the first method, additional income is gained by a scientific organisation or team, and the work is delivered against a specific order or commission. In Russia, the clients of such research projects are funds specifically formed for this purpose, and specific government departments. Examples include: the Russian Federation government programme "Energy saving and increased power efficiency for the period until 2020", projects of Rosnanotekh State Enterprise, local projects "Modernization of illumination systems in higher education institutions", the Ministry of Culture, the Ministry of Development and Trade, etc. Examples of foreign collaboration between universities and funding agencies shows that without an announcement of special state programmes, research and design projects undertaken by universities for production companies, are systematically and effectively stimulated by state funds or by interstate grants (for example, *TEKES* in Finland). In Finland, applications of manufacturing enterprises for new developments are received by the relevant ministry and primarily assigned to the appropriate university faculties.

Despite direct appeals of the President and Prime minister, small Russian enterprises are hardly involved or brushed aside in such collaborative efforts. During last three or four years, the system of competitive tenders for researches and production of devices has become more transparent but remains unsystematic and reflects some of the shortfalls of Soviet period economics.

It is not always possible to evaluate the efficiency of the state investments in scientific research due to the costs and the process of transforming investments into innovative technologies.

– ***Creation of new hi-tech companies*** (businesses)

This is the most widespread form of the "commercialisation project". Its differentiating factor is the aim of developing a product based on results of research and development results, creating a new company. Risk is a distinctive feature of such projects, arising from the nature of innovative products. Some of the leading companies in this branch are Optogan Joint-Stock Company, Svetlana-optoelektronik Joint-Stock Company, TKA STE Open Company, Arhilait Test laboratory (TL), etc. These companies using innovative technologies, commercialise them successfully and occupy an essential part in their market segment.

– ***Licence sale*** (rights for use of research and development results)

According to the information available, this is a poorly developed method of commercialisation in Russia. However, it may be that some developers fail to advertise their use of third party intellectual property.

Global practice convincingly confirms that the mutually beneficial commercial interaction of all participants in transforming scientific results into market products is the most effective method for the promotion of innovation in practice. The fastest commercialisation is provided by technology transfer of market-ready solutions.

There is a very strong monopoly of supervising state enterprises and organisations in Russia. The state standards bureau Gosstandart, supports research institutions, and allocates state funds mainly to them. The absence of competition and of general discussions on the standards issued leads to an obvious decrease in quality. Referring to a harmonisation with the international standards is incorrect; all countries participating in the harmonisation process introduce their corrections of terms, concepts and limitations, which are nationally specific following a thorough consultation with a wide network of national experts. Only in Russia issuing "customised" state standards is admissible. Analysing approved national standards, experts recognise not only obvious technical and scientific errors, as well as typing mistakes, but also passive references to latent customers of separate provisions and standards. This is the face of Russian commercialisation!

Unfortunately, a determining factor is the frequently unrecognised danger to health within legislative standards. After the Building regulations were issued, general quality control of information reflection devices (displays) began in Russia. This control prevented the import of poor-quality products. After the Building regulations SNiP 23–05–95 were issued, control processes were instigated for the UV radiation component, light ripple and minimum workplace illumination levels. Then a reverse trend occurred: a new GOST (Russian state standard) eliminated light ripple effect from the parameters necessary for control, and consumer interest for pulsometers sharply decreased. But the negative influence of ripple influence is well documented. It has a negative impact on the brain, and as a consequence, causes an increased fatigue and nausea.

As a result of successful commercialisation, measuring instrument manufacturers, in particular TKA STE Open Company and OPTEK Joint-Stock Company, have become global market players for analytical, photo and colorimetric products and almost dominate a large sector of the domestic market in Russia. At the same time, these enterprises are scientific partners of many research institutions of the country. All of this is achieved despite a scientific and economic counteraction of enterprises of the Agency of Technical Control and Metrology.

It is difficult to predict long-term determine development directions for measuring devices and illumination systems. But whatever new lighting technologies emerge in the future, their development will flow along recognised pathways: start-up companies based on new technologies will appear ("market draft" model), technologies of the developers will improve, and third-party developers will be acquired ("technological push" model). New young businessmen/businesswomen and scientists will arrive; they will learn from the mistakes of our time and will embrace new methodologies, which will inevitably appear in the future.

Glossary

– Innovation activity is the process of structured work converting innovation into products, and introducing these onto the market for commercial application.

– Innovation strategy is the development strategy of a company, through which its response to current market demands and its competitive advantages are ensured due to continuously updating production technologies, as well as due to the indepth knowledge and abilities of personnel.

– Commercialisation and technology transfer (of research and development) is any activity, the purpose of which is to generate an income from the application of scientific research results and scientific competences.

– Commercialisation is the method of transforming a research outcome into a market product.

– Marketing is a control system of industrial and sale activity of companies based on an integrated market analysis.

– Management is administration of production and technology.

– Market segment is a group of customers with similar interests and similar responses to marketing activities.

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ILLUMINATION OF THE SAINT PETERSBURG UNDERGROUND NAMED AFTER V.I. LENIN

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ABSTRACT

Some results of visual appraisal of illumination of St. Petersburg underground metro system are discussed. The main purpose of the research was to understand the main features of this system's operation, its merits and shortcomings. Based on measurements taken and analysis of the results, conclusions are drawn about failing to meet illumination standards, inappropriate selection of light sources and luminaire optical systems. A need for replacement of existing light sources for new ones more suited to use in the tough operating conditions of the underground is discussed.

Keywords: examination, architectural illumination, underground, light emitting diodes

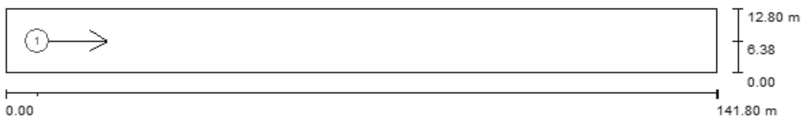
The St. Petersburg underground metro system named after V.I. Lenin is considered to be one of the most beautiful underground systems in the world. It drastically differs from underground networks in London, New York, Parisian and from the first line of the Budapest underground by its architectural image. In aesthetic terms, the European underground systems were designed to be utilitarian, reflecting the industrial architecture of the period in which they were built. In contrast, the St. Petersburg underground was envisioned by the architects as a system of underground palaces for people, who inspired the development of this most democratic type of transport. There is no other underground network anywhere in the world with such an abundance of valuable stone and sculpture elements, paint and mosaic panels, as well as decorative reliefs in the station halls. St. Petersburg's underground system can be only compared with the Moscow metro by beauty of its interior architectural decoration.

In any underground transport network, the light factor is especially important. In St. Petersburg however, besides ensuring passenger safety, it was also important to illuminate the architectural character of each station. This is an example of a situation where the architectural and functional components of illumination are inseparable.

Investigation of illumination installations (LD) of some St. Petersburg underground stations was initially carried out in 1980 [1]. A panel of examination experts participated made up of light engineers and architects. At that time point, the illumination level reflected the normal standard at almost every surveyed station. At the time of this investigation, interviews were already revealing that there were some illumination problems, which were causing discomfort to passengers at the stations.

Illumination standards for underground constructions were first prescribed in the Underground Construction Regulations and Rules, 1950 and since then did not change for a long time. Illuminance level on a platform edge was set to no less than 150 lx, the same level was set for escalator steps. This level ensures passenger safety and was the necessary minimum for a long time, which was strictly observed when building underground stations.

In 2004, illumination standards for stations were changed (Construction Regulations and Rules СП 32–105–2004). It has become necessary to increase



Scale 1:1014

UGR list of calculated points

№	Marking	Position [m] X	Y	Z	View direction [°]	Significance
1	UGR calculated point 1	6.100	6.377	1.200	0.0	/

Fig. 1. UGR observer (result review), Baltiiyskaya station

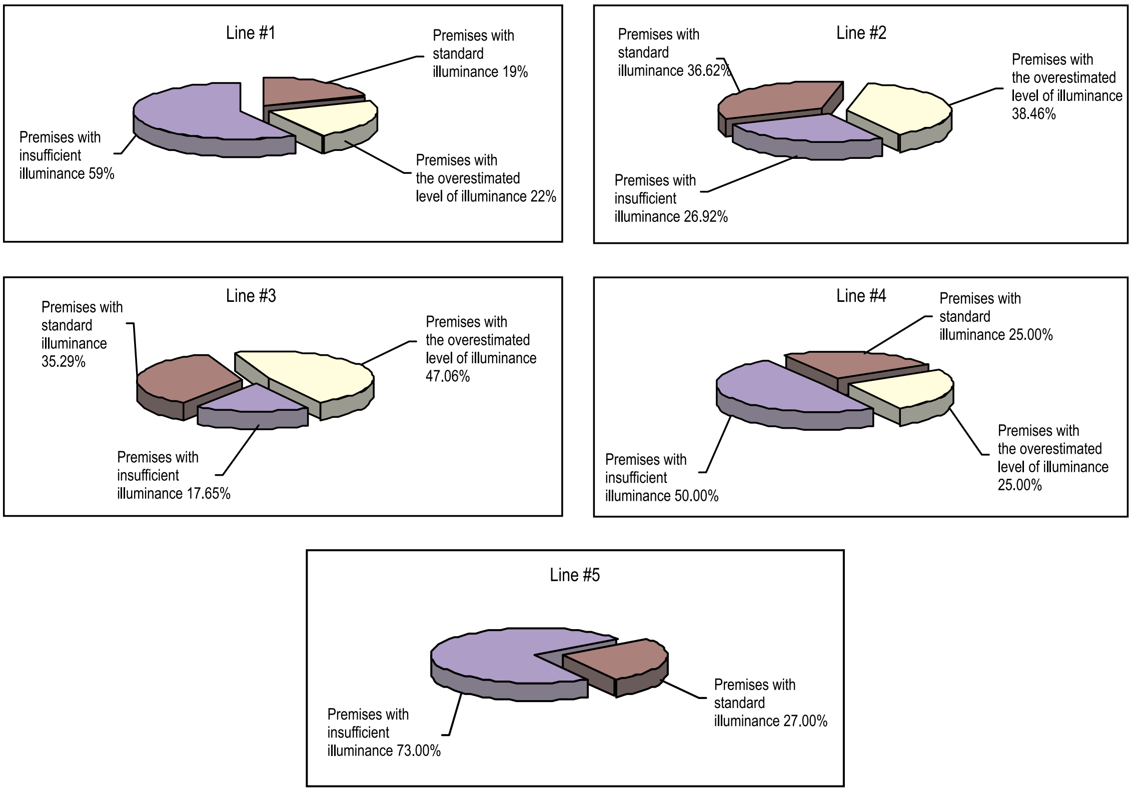


Fig. 2. Distribution of spaces on different lines of the underground by level of illumination

the illuminance in middle and platform halls to 200 lx. As a result, outdated light sources (LS) at some stations were replaced with more energy-efficient, and in some cases, additional illumination devices were installed.

This focus on underground illumination issues was caused by the following factors:

• A revolution in the world of LSs and the need for them to be photobiological safe when operating within the underground system;

• Increased duration of the man-mande influence of the underground medium on the passengers, improved knowledge about light's influence on human eyes and hormonal system (see e.g. [2]);

• Changing requirements of underground object illumination quality and comfort as a result of better understanding the influence of illumination on a person and on the historical value of underground architectural objects; developments in the understanding of illumination quality for objects of architectural beauty, painting and sculpture within the underground system;

• The growing problem of power consumption and environmental safety in the context of extending underground lines, insufficient reliability of fluorescent lamps (FL), vandalism of luminaires with FLs in metro cars, escalators and inspection pits of the depots;

Table 1. *Voltcraft* illuminance measurement instrument data

Measurement intervals		0.1–50000 lx (four measurement intervals)
Within an interval	200 lx	Resolution 0.1 lx
	200 – 2000 lx	Resolution 1 lx
	2000 – 20000 lx	Resolution 10 lx
Measurements per second		1.5
Uncertainty	Less than 10000 lx	± 5%
	More than 10000 lx	± 10%

Table 2. Illuminance standards for different passenger spaces of the underground (according to СП32–105–2004)

Room	Illuminance regulating plane	Horizontal illuminance, lx
Central and platform halls	Floor level	200
Ticket office hall		200
Area before escalator entrance		100
Escalator racks and stair flight	Step rack level	100
Corridors between stations	Floor level	100
Entrance corridors and passages under streets		75

• Problems of light and information pollution of the underground.

Influenced by all of the issues listed above, the main requirements of luminaires and LSs used for architectural illumination of metro stations [4, 5] were formulated. They addressed LS ecological safety; increasing LS energy efficiency; operational reliability (life time should be more than 80000 hours without LS replacement); LS dimensions; illumination quality; LS compatibility and integration with current safety systems.

Visual surveys of illumination system on the St. Petersburg underground network showed that 80% of the luminaires are located in hard-to-reach places, and so obstruct replacement of failed lamps and luminaire cleaning. Nevertheless, LS replacement is performed in due course, and the luminaires are regularly cleaned.

Illuminance measurements were performed in almost all stations, in the middle of platforms and platforms halls, and selectively in entrance halls and passages, as per the requirements of the standard GOST 24940–96. A digital luxmeter *Voltcraft MS-1300* (Table 1) was used. It is important that the maximum deviation of horizontal illuminance from the standard is no greater than ± 20%. The measurements were taken with all luminaires switched on, during underground working hours. Illumination facilities, LS and luminaire types, as well as the decoration of surfaces were described. The measurements of horizontal illuminance were carried out in check points at floor level (G- 0,0 is a horizontal plane level of 0.0 m from the floor), and the results were compared with the standard parameters established in СП 32–105–2004 (Table 2).

Unified Glare Rating (UGR) parameter was computed using DIALux 4.11 software for the all surveyed rooms. This did not suggest that amongst the tested stations there were any where illumination could produce a blinding effect on passengers. There are no sources of glare in observers' field of vision at these stations, because 80% of the architectural lighting installations represent LDs of reflected light, and most of the luminaires are "hidden". An example of the calculation result for one of the stations is presented in Fig. 1.

It can be seen from the results of illuminance measurements, that illuminance standards were not observed at more than in half of the surveyed spaces at the stations, on each line of the underground. The reason of this was unsatisfactory LD service management.

Table 3. Results of illuminance selective measurements in the entrance halls of underground stations (E_{fact}) at two levels from the floor (0.8 and 0.0) and the corresponding standard parameters (E_{st})

Station	Entrance halls				At ticket offices			
	E_{fact} (G-0.8), lx	E_{fact} (G- 0.0), lx	E_{st} (G-0.0), lx	Corre-spond-ence with standards	E_{fact} (G- 0.8), lx	E_{fact} (G- 0.0), lx	E_{st} (G- 0.0), lx	Corre-spond-ence with standards
Vyborgskaya	-	337			-	349		Yes
Polytechniche-skaya	-	276		Yes	145	87		
Devyatkino	113	75	200		-	45	200	No
Ozyorki	50			No	57	-		
Udelnaya	178	140			51	38		
			Meets standard	40%			Meets standard	20%

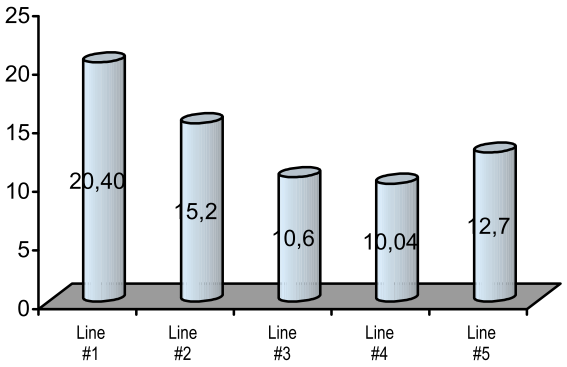


Fig. 3. Electrical energy consumption by illumination devices on St. Petersburg's underground system, GW·h/year

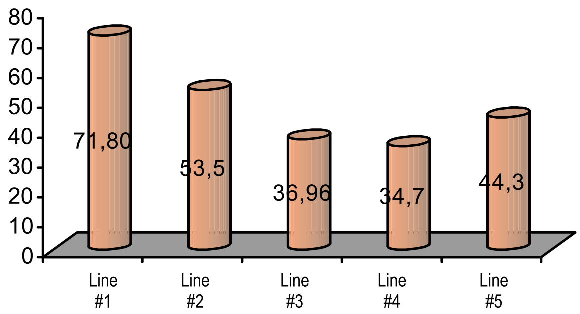


Fig. 4. Approximate costs of illumination device operation (electric power cost, purchase cost, replacement and recycling cost of the lamps), million roubles per year

The application of high power HPSL caused excessive illuminance at Novocherkasskaya, Prospekt Bolshevikov and Obukhovo stations, exceeding 500 lx; these stations were bathed in yellow light.

Fig. 2 shows in an equity ratio for the rooms with insufficient, redundant and standard illuminance levels. At the stations with an insufficient level of illuminance a twilight atmosphere prevails, which is dangerous for passengers. In this case, redundant illuminance is a result of inappropriate LS selection.

A visual survey of central and platform hall LDs has shown both advantages, and disadvantages of the illumination system.

Advantages: full transfer to CFLs from ILs. LDs are in a good state, all LSs are working and are replaced in time. Regular cleaning of luminaire diffusers is carried out. Illumination from behind cornices on Line 2 stations uses FLs with identical colour rendition and high chromatic temperature, therefore, with timely LS replacement; the architectural image of the objects is sustained. There are no glare sources within the passengers' field of vision. Photo cells for LD control are installed at new stations.

Disadvantages: illumination at the most stations is controlled by a simple mechanical switch, or by a timer. LDs operate 24 hours a day even when they are not needed, in case of any reconstruction or maintenance work (according to the operating personnel). For illumination from behind cornices, MAL lamps are used in the central halls at the Pionerskaya, Zvyozdnaya and Sennaya Ploschad stations, which make the illuminance of the design surface spotty and greenish. The luminous flux ripple ratio

Table 4. Results of illuminance measurements in escalator areas of the underground

Entrance halls	E_{fact} (G- 0.0), lx	E_{st} (G- 0.0), lx	Correspondence with standards
Vyborgskaya	180	100	Corresponds
Polytechnicheskaya	200		
Devyatkino	75		Does not correspond
Ozyorki	50		
Udelnaya	138		Corresponds
		Meets standard	60 %

Таблица 5. Correspondence of illuminance actual values with standard values set. Passages

Passage	E_{fact} (G-0.8), lx	E_{fact} (G- 0.0), lx	E_{st} (G- 0.0), lx	Corresponds
Vyborgskaya	40	34	100	Does not correspond
Ploshchad Vosstaniya	160	110		Corresponds
Sadovaya	150	100		

of MAL lamps reaches 70–80 %, which can lead to development of a stroboscopic effect. Standard illuminance levels are not met in 81 % rooms of Line № 1 central halls. At Zvenigorodskaya station, different chromaticity MHLs are used, which violate the general style of the station. In the central hall of the Volkovskaya station, illuminance level is intolerably low at 71 lx, and on the platforms it is only 52 lx, which makes standing close to the platform edge dangerous for passengers.

It can be seen from Table 3 that the general illuminance at floor level (working plane) corresponds to the standard parameters in 40 % of surveyed halls, and in 20 % of surveyed ticket office areas. This means that illumination along the perimeter of the entrance hall often insufficient, and it is here that cashiers work counting money, which requires attention and greater levels of illuminance. Table 4 shows that illuminance standards in surveyed escalator areas are met in 60 % of the cases.

The management of the St. Petersburg underground network decided to illuminate the passage to Zvenigorodskaya station using luminaires with light emitting diodes (LED), which now being piloted. Luminaires with LEDs are very suitable for underground illumination from behind cornices due to the absence of mercury, their reliability and durability. In this case, they are hidden from the observer's eyes, which eliminates blinding effect, and their service life exceeds 25 000 hours. These features, in the context of time-consuming LS replacement, in underground conditions, makes luminaires with LEDs one of the best options for the illumination of the underground. From the illuminance measurement results for passages (Table 5), it can be seen that illuminance is approaching the standard in more than 60 % of surveyed spaces.

Illumination of St. Petersburg's underground system consumes about 69 GW hours per year. 78 % of this is accounted for by luminaires with FLs, 20 % – with MAL lamps and 2 % – with HPSLs (high-pressure sodium arc lamps). Some other data are provided in Figs. 3 and 4.

It is clear that a more appropriate choice of lighting facilities will make it easier to meet illumination standards, and at the same time cut electricity and LD service costs on all underground lines. The use of luminaires with LEDs will become an effective solution for the underground metro system.

CONCLUSION

- There is a need to reconstruct the illumination system of St. Petersburg's underground network in order to retain illumination characteristic specified by its design as much as possible;
- The luminaires used should be ecologically safe, of sufficiently small dimensions, be compatible and integrate with safety systems;

• The LSs used should be of high energy efficiency, have a long service life (more than 8000 hours), high colour-transmitting properties and stable characteristics under tough operating conditions;

• It is necessary to install a control system of the architectural illumination of the underground, because station and platform illumination often remains switched on unnecessarily.

We are grateful to the administration and the team of the St Petersburg underground named after V.I. Lenin for the opportunity to carry out illuminance measurements and analysis of the illumination system.

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