The analysis of modern low pressure amalgam lamp characteristics

Michiel Van der Meer (Philips Lighting), Fred van Lierop (LSI/Lighttech), Dmitry Sokolov (LIT)

Over the last 10-15 years the market of manufacturers of UV equipment for water, air and surface disinfection, as well as the technology of UV disinfection has made a significant progress. It is valid to say that the market of UV equipment manufactures has shaped with the main players being Trojan (Canada), Wedeco Xylem (USA-Germany), LIT Technology (Russia/Germany), Calgon Carbon (USA), HALMA Fluid Technology Group and many others.
The rapid growth of UV technology is to a large extent caused by successful development of the irradiation source technology at a wavelength of 254 nm – a low pressure amalgam lamp. We can remember that even 10 years ago the main source of irradiation was lamps with power up to 100 W generally made of so called soft glass. There were also similar mercury lamps made of quartz glass, which we know as standard low pressure mercury lamps. The developing technology has brought to live new sources with powers of 200, 300, 500 and even 900 W. They made it possible to significantly reduce capital expenses by minimizing costs of UV systems which are now equipped with less number of lamp-units but maintain the same level of disinfection and water flow. The largest producers of modern low pressure amalgam lamps are Heraeus Noblelight (Germany), LSI/Lighttech (USA/Hungary), Philips Lighting (Belgum/China), LIT (Russia), Wedeco Xylem (Germany), UV-Technik/Hoenle group (Germany), First Light (USA) and some others.

The purpose of this paper is to show how some lamp parameters such as pressure or gas composition affect on the work of modern low-pressure amalgam lamps. Which ones are able to change the effectiveness of amalgam lamps and what is the range of such changes? Where is the maximum attainable efficiency lamps and how this parameter affects on the energy efficiency of whole system for water or air disinfection?

The «heart» of any UV system is a UV source and the present paper is devoted to the most common and well-known UV source – a low pressure amalgam lamp. What is an amalgam lamp? The UV source in low pressure mercury lamps and amalgam lamps that are commonly used for disinfection is a low pressure arc-discharge in mercury and inert gas vapors. They differ only in the source of mercury vapor - mercury lamps use a small amount of liquid metallic mercury, while amalgam lamps rely on amalgam that is a hard alloy of mercury with metals. The optimum mercury vapour pressure is 0.8-1.5 Pa for mercury vapor and 50-500 Pa for inert gases (mostly neon or argon or their mixture). Under such conditions, 30-40% of discharge lamp power is converted into UV radiation at the mercury resonance line with a wave length of 253.7 nm that is very close to the maximum of the germicidal curve. Irradiation spectrum is linear (see Figure 1). 90-98% of all discharge irradiation is UV radiation at 185 and 254 nm wavelength.

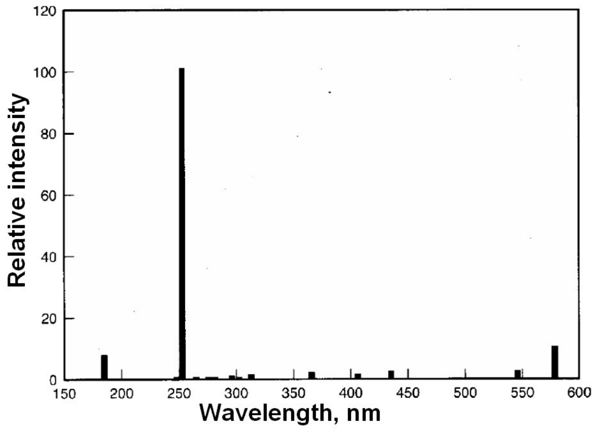

Fig.1. Spectrum of mercury low pressure discharge (100% level is 254 nm line)

It is worth of note that lamp characteristics of different lamp producers are often very similar. For instance, the comparison of common and well known 300W lamps, such as UV3000+, XPT235, DB300, UVI260, GPHVA1554T6 shows that the values of lamp current, power and efficiency UV output are very similar. It is true that the lamp current varies form 1.8 to 2.0A, UV power - from 87 to 95 W, electrical power – from 230 to 260 W. Thus, we can conclude that the efficiency of these UV source would be almost the same - 35-38%.
When power and operating lamp current go up the characteristics will change. Today the operating lamp characteristics are the following:
Power – up to 1 kW;
Lamp life – 12000-16000 hr;
UV output drop at the end of lamp life– 10-15%.
Many lighting companies actively cooperate with each other and share technical information about lamp parameters since such vital parameters as UV output, efficiency of source, lamp life, UV output drop during operation are essential for the customer and often specified in tender requirements for supply of UV equipment. Almost all of the above companies are IUVA members and they all contributed to a standard protocol for measurement of low pressure amalgam lamps [1] that is based on a so called Round Robin Test. This has strengthened the cooperation between the companies and has facilitated better exchange of information.

It is important to note that UV drop reduction/maintenance or extension of lamp life are feasible tasks as they are technological tasks for lighting engineers. What still remains an issue is the lamp efficiency.

What would be the ideal UV lamp for a practicing engineer? We can imagine a dark-to-eye quartz tube with the temperature of the lamp tube close to room temperature. 100% of supplied energy in such lamp would be converted into invisible UV irradiation. Certainly this is not possible as there would be losses caused by other processes such as heat, ionization and near-electrode loss, irradiation at another lines losses (including visible light). Is the value of 35-38% large or small? Comparison with other light sources has proved that this is a very high efficiency and this is one of those very rear cases when nature helps us because the 254 nm line is close to the maximal efficiency of the germicidal curve. An alternative to this UV area could be xenon excimer sources with respective phosphor. Their efficiency is only 10-20% (with optimal dimensions and power up to 100W)[6]. Another alternative is light emitting diodes with a wavelength of 260-270 nm. But their current efficiency does not exceed 3%.[7]

Let us take a brief look at factors affecting the efficiency of low pressure amalgam lamps.

In terms of physical processes that take place in a lamp there are the following affecting factors:
-lamp current (and its frequency);
-diameter of lamp tube;
-thickness of tube wall;
-tube coating;
-filling and pressure of ballast gas;
-isotopic compound of mercury;

In our view, it is not necessary to dwell on physical aspects of various gas-discharges impacting UV output at 254 nm, therefore, we will focus on the essentials only, for more information please see Appendix 1.

Mercury vapor pressure
Does the mercury vapor pressure affect UV output in amalgam lamps? Yes, it surely does – the pressure determines the number of excited mercury atoms and thus determines UV output. However, regardless of other factors it is safe to say that there is a certain optimal pressure for each lamp. A way to achieve it is solely an engineering task that could be addressed, for example, by maintaining a certain temperature of amalgam. Every manufacturer would solve the task on a case-by-case basis (by using muticomponent amalgams, pellet technology, cold point). It does not seem possible to obtain a UV output that is higher than a certain maximum when the mercury vapor pressure is optimal. At higher pressures an increasing amount of UV will be absorbed in the plasma (so called self absorption).

Gas filling and pressure
The decisive factor for excitation of the required level of 6^3P_1 is the electron temperature of plasma. The purpose is to achieve its optimal value. Could the discharge in mercury vapor work without ballast gas at all? Certainly, it could. Moreover, the first mercury lamps worked exactly this way. Ambipolar diffusion makes electrons and then ions move to the walls rapidly in the absence of ballast gas. Plasma maintains a high rate of ion-electron pairs, which increases the electron temperature. High electron temperature (that means high energy of electrons) allows to introduce power not only to the line of 254 nm but to other undesirable lines, which causes losses. The neutral gas atoms act as a “moderator” and reduce diffusion of particles to the wall. The gas pressure also affects the electron temperature for the same reasons. The acceptable pressure area is quite narrow due to short lamp electrode life – the electrodes are destroyed quickly under low pressure (See App 1). Next to this, the buffer gas is used as a means to slow down the electrons and thus making the Hg-excitation process more efficient.

Lamp coating
What is the purpose for coating of the inner lamp surface? One of the main lamp characteristics is UV output drop at the end of lamp life. To ensure a proper disinfection level even after 12000-16000 hours of operation the UV system is designed to manage any potential slackening of UV output. Of course, the UV source is more practically efficient when UV output drop is small. Being an effective protector of quartz glass against discharge plasma, coating is a good solution for the issue.

The influence of lamp **protective coating, diameter of discharge tube and its thickness** is discussed in more details in App. 1. Here we will look at the role of lamp current and its frequency as one of the essential factors of operational efficiency of low pressure amalgam lamp.

Current, frequency and waveform

Lamp current

Whatever the lamp filling, the UV output grows first when current increases and then it becomes saturated. This happens due to increasing number encounters of particles with excited mercury atoms. (For more information on the influence of lamp current please see App. 1).

Lamp current frequency

The influence of lamp current frequency has been studied many times. It is known that the main loss during low pressure discharge is caused by ambipolar diffusion to the tube walls. The ambipolar diffusion time is millisecond. This time is less than period of industrial supply voltage with a frequency of 50-60 Hz. That is why the discharge dies out at the end of each half-period and it ignites at the beginning of the each next half-period. Under these conditions the forms of discharge current and lamp voltage are not the same. Although an electromagnetic driver is commonly used, it offers an outdated solution due to small number of On/Off cycles, relatively short lamp life, smaller energy input to plasma and low efficiency and cosφ. Furthermore, it is understood that low frequency switching at 50 or 60 Hz will give the plasma and electrodes too much time to cool off during current reversal. When the plasma and electrodes cool, a larger supply voltage is required to 're-start' the lamps. All this results in reduced efficiency. By changing to high frequency (sinusoidal or square wave) these effects can be reduced to a certain amount. Very high frequencies are not known to reduce these effects further.
In practice, electronic ballasts are used for powerful amalgam lamps. The ballasts have sinusoidal current and frequency of 20-60 kHz. This eliminates the above disadvantages of electromagnetic ballasts. However, the further increase of frequency is not promising. First, this does not significantly increase the UV output of 254 nm line, since near-electrode losses can not be reduced infinitely. Second, this causes large capacitive loss in wires. The practical limit is around 60-70 kHz, but in reality 30-40 kHz frequency is used because of minor difference of discharge efficiencies of these frequencies and based on necessary reserve for dose pacing systems which implies a very high lamp current frequency.

Current waveform

also affects the discharge characteristics. For example, square waves such as meander can be used instead of sinusoidal that theoretically can increase efficiency of energy input to discharge plasma. However, it can be shown that additional efficiency is minor for 254nm line and the use of this waveform may create significant losses. Fourier series of such a waveform gives a number of higher harmonics, i.e. 150 kHz, 250, 350 etc. The currents of such harmonics will have significant loss in the ballast-lamp wires and reduce total efficiency of a system. This approach may be feasible only when the ballast is installed in close proximity to a UV lamp, which is not always convenient to the customer.

In our discussion above, we talked about characteristics that mainly determine the efficiency of lamp operation. What is the efficiency of a UV lamp? According to the classical definition, It is a ration of total UV flow to lamp power:

$$\eta = \frac{\Phi_{254}}{\Phi_{el}} * 100\% \quad (1)$$

As already mentioned above, there are many factors that limit UV output. Theoretically efficiency of gas discharge in mercury vapor could be very high [3]. It can be shown that it is possible to reach >50% efficiency due to special gas filling and low current density, but it is useless in practical terms due to insufficient life time or low UV output.

It is well-known that lighting companies like LightTech, Philips and Heraeus are the main suppliers of amalgam lamps for leading producers of UV equipment for water, air and surface disinfection in the world. The designers of UV equipment trust the data provided by the supplier and design UV equipment based on important characteristics such as UV output, source electrical power and its dimensions. Beyond all doubt, the designer provides certain margins like:
-10-15% aging margin;
-ballast efficiency margin which is usually not more than 10% for amalgam lamps;
-10% common margin which implies some possible measurement variation and maximum UV irradiation given in catalogues rather that nominal value that could be less in real conditions of water or air treatment.

Generally, calculation of the electrical power of UV systems shows that the power of UV lamps with regard to and ballast losses accounts for 90% and more of the total UV system:

$$W_{Total} = N(W_L + dW_D) + W_{E\,l}, \quad (2)$$

Where:
N – number of lamps;
$W_L + dW_D$ - power of lamp and ballast;
$W_{E\,l}$ - certain additional power for power supply of a controller, control panels, sensors etc. As a rule, $W_{E\,l}$ is very small comparing to the total power consumption.
It should be noted that, the analysis of UV equipment for water disinfection of global producers has shown that formula (2) is almost always true.

Summary

The data provided by lighting companies are essential for designers and producers of UV equipment. Based on extensive experience, theoretical researches, joint laboratory efforts to measure lamp parameters and taking into account the above considerations, we state that efficiency of modern powerful UV sources is 30-40% at the beginning of lamp life. These data are well known, verified by numerous mutual measurements and published in official catalogues of the above mentioned companies.
Sometimes manufactures of UV equipment declare ultra-high lamp efficiency for marketing purposes and knowingly or unknowingly mislead the customer. For example, they may specify lamp efficiency without ballast losses and apply this efficiency for the whole UV system. Or they give the data for specific ballast which can provide such efficiency only in certain circumstances (for instance, near the lamp, which is often inconvenient and not used) etc.
The customer should remember that estimation of energy efficiency of a UV system is based on total power consumption of the UV system and accurate consideration of all its operation modes. He should not be taken by the above marketing steps, where *“The pure and simple truth is rarely pure and never simple.”— Oscar Wilde.*

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Appendix 1
Factors affecting UV output at 254nm

Mercury vapor pressure

Mercury vapor pressure is not a key point for UV output. There exist some techniques designed to maintain the optimal vapor pressure (multicomponent amalgams, pellet technology, and other ways to locate amalgam behind discharge). It is true that when mercury vapor pressure increases while other discharge parameters remains the same, UV output increases due to increasing number of exciting and irradiating atoms. However when a certain optimal level is exceeded the efficiency decreases again, see Figure 2. This is caused by the reabsorption of resonance radiation and the increase of effective lifetime of the excited level as well as the drop of electron temperature. Some of the energy is lost when excited atoms encounter each other. The range of 0.7-1.5 Pa is optimal [3].

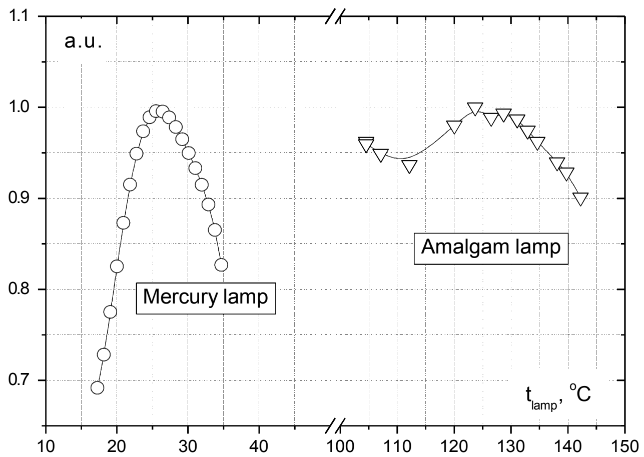

Fig.2. Relative UV output depending on liquid mercury or amalgam temperature.

Lamp filling
Gas filling and pressure

The sole role of the inert gas in the wide range of ambient conditions is to transport particles in the volume and diffuse charged particles to the tube walls. Thus, the pressure of buffer gas determines the death process of mercury ions and electrons and the pressure of mercury atoms determines the ionization level, optical and largely electrokinetic characteristics of discharge. Such allocation makes it possible to vary selected characteristics substantially and obtain a number of new discharge properties. It is the low pressure discharge of mercury vapor and inert gas mixture that is used in UV sources due to efficiency capability to convert electrical power into discharge radiation.
The key function on inert gas is to reduce the diffusion rate of electrons to the lamp wall. By pressure adjustment the electron temperature can be regulated to the optimal level when the energy electron excitement and mercury atoms emission is much higher than energy loss for elastic collisions. Excitement and emission loss depend exponentially on the electron temperature and elastic interaction loss depends linearly. The electron temperature should not be very high since the task is to get exited mainly 6^3P conditions and not to get significant excitement of the higher levels. Reduction of inert gas pressure to a certain limit increases the efficiency of UV irradiation by discharge and energy distribution in irradiation spectrum can vary. However, this dependence is non-monotonic. One of the reasons of this is the above mentioned affection of inert gas upon the processes of resonance radiation absorption. When pressure is too low, the electron and ion flow to the walls intensifies and energy loss for ionization grows.
When the pressure is below 1 torr the life time of oxide-coated cathode becomes a restrictive factor. Due to high diffusion coefficient particles of barium oxide “move” to plasma and reduce electrode life time to unacceptable values. Thus, the typical range of the buffer gas pressure is quite narrow – 0.8-2 torr. The energy of moving ions will also be higher at lower pressures (less collisions with buffer gas) and this will also result in increased Barium-oxide consumption.
The higher temperature required for optimal UV output can be achieved by changing a buffer gas with the one in which the diffusion rate of ions and electrons is higher. Also lower pressure can be used for the same tube diameter. In fact, the rate of electron and ion disappearance depends on the variation of ambipolar diffusion coefficient in inert gas which is determined by ion mobility in this case. The values of mercury ion mobility in the top three lightest gases at 0°C and pressure 100 kPa (760 mm of mercury) approximately amount to:
He – 19.6 $cm^2/(V\cdot s)$;
Ne – 5.9 $cm^2/(V\cdot s)$;

Ar – 1.85 $cm^2/(V\cdot s)$.

The mercury ion mobility in krypton and xenon are even less. The lighter gas has the higher mercury mobility in it. Thus, the electron temperature and the saturation level of UV output are maximal in helium and minimal in xenon. Xenon and krypton are not good for practical purposes due to low UV output, see Figure 3. Helium is very fluid and can be used in theory only. Argon, neon and their mixtures are used in practice. (Of course, the gas purity is an important factor).

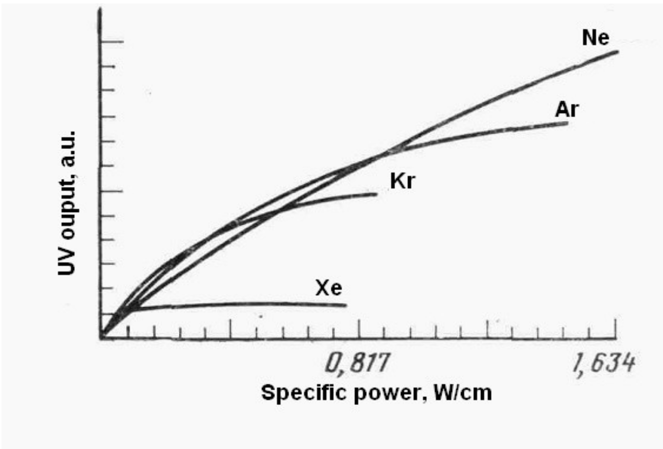

Fig.3 UV output depending specific power for different ballast gases.

Lamp current

When the lamp current increases the efficiency of UV generation by discharge drops down. The reason for this is that the electron density increases and the elastic collisions of electrons with atoms of inert gas and mercury increase the gas heating. Also, the electrons quench intensively the excited condition of mercury atoms by electrons during nonelastic interactions of the second kind. Another and the most important reason is the reduction of electric intensity and electron power due to the increased density of metastable mercury atoms and the enhanced role of stepwise processes. Hence the UV output first increases when current increases and then becomes saturated. In reverse, it can be argued that the efficiency will increase when the current density decreases. The resulting UV output will however also be reduced, resulting in a technically unfavorable lamp system.

Change of discharge diameter

Diameter change affects the discharge in two ways. On the one hand, the reduced diameter increases the loss of charged particles. On the other hand, it increases the current density. When the diameter of a discharge tube is enlarged the efficiency first goes up as the loss of charged particles goes down and then the efficiency goes down as the electronic temperatures drops.

The wall thickness of tube is mainly determined by mechanical strength and UV transmittance of quartz glass. The minimal thickness is most advantageous in terms of UV output since the UV obeys the Beer-Lambert law taking into account UV transmittance (quality of quartz glass) $I/I_0 \lceil e^{\lceil\lceil l}$.As a rule, the wall thickness is close to the minimal but it is still sufficient for the reason of mechanical strength. It is 1-2 mm in practice. UV transmittance of good quartz glass is 87-89% for 1 mm of thickness. The UV transmittance of pure quartz glass could be more that 90% but this glass has special additives (100-200 ppm TiO_2) to block 185 nm line. In this case the 254 nm line is slightly reduced.

Lamp coating

The mechanism of darkening was studied and discussed in [4,5] and is associated with the formation of mercury oxide on the inner surface of the quartz tube. This can be explained by the ambipolar diffusion which is caused by the formation of an electrical field between the plasma column and the tube wall. The mercury ions are accelerated in this electrical field, gain kinetic energy from it and impact into the quartz wall. This leads to a formation of Hg-O bonds. Mercury oxide (HgO) strongly absorbs UV radiation. So, the mercury oxide layer with a thickness of only 10 nm absorbs app. 50% of UVC radiation emitted by the discharge.
There are many types and approaches to provide a protective coating. The main principle is to protect the quartz wall by a transparent layer more chemically stable to mercury ions. Usually, the aluminum or yttrium oxides are used. Generally, the structure of layers obtained in different coating methods can be divided in two groups: nano-particle layers and meso-porous layers, see Fig 4 and Fig 5.

Quartz

Coating

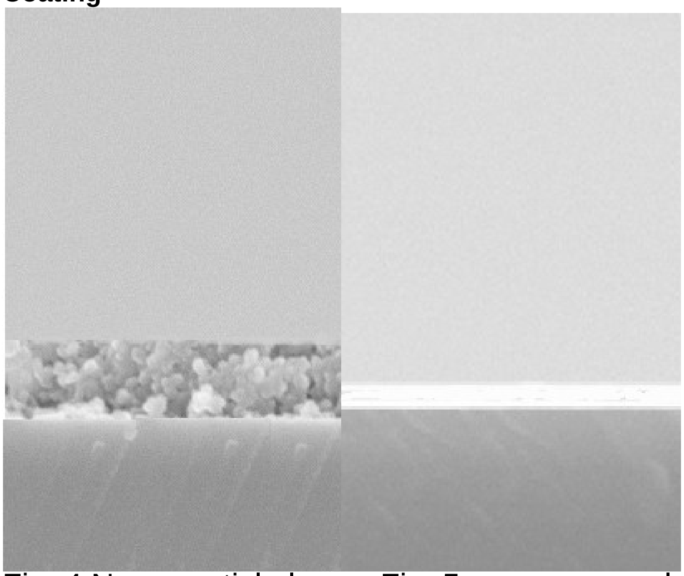

Fig. 4 Nano particle layer. Fig. 5 meso-porous layer

Each method has its own advantages. So, the coating method choice done by the lamp manufacturer is based on the comparison of required lamp parameters, lamp reliability in terms of lifetime and production costs.
The nano-powder coating is extremely cheap, is fast to apply, can be burnt in at a low temperature. The transmission of the layer is high enough for usage in UVC-lamps (253.7 nm) but not sufficient for VUV-lamps (184.9 nm).
The meso-porous layers are prepared in so called “sol-gel” routine. They are closed, provide a very high transmission up to the VUV region. The applying procedure requires a certain technological knowledge and is more complicated in comparison to the nano-powder technique.
A high power amalgam lamp needs a protective coating. Without it the lifetime is not acceptable for any industrial application. The UVC depreciation during the lifetime of a coated lamp is connected with the kind of protective coating, lamp filling, lamp current load, etc. and lies in the region from 10 to 20 percent after 12000 to 16000 hrs, see Fig. 6.

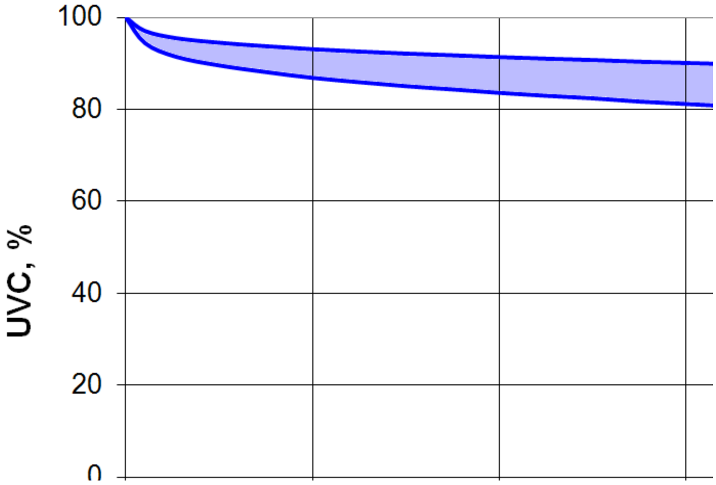

Fig6. Typical curves of UV output drop for powerful amalgam lamps.

Isotopic compound

There are seven isotopes in natural mercury: (^{196}Hg(0.146%), ^{198}Hg(10.02%), ^{199}Hg(16.84%), ^{200}Hg(23.13%), ^{201}Hg(13.22%), ^{202}Hg(29.80%), ^{204}Hg(6.85%). Due to that fact the effective trapping of the resonance radiation in natural mercury is less compared to the trapping in mercury if only it could consist of one isotope [2]. The study of impact of mercury composition upon resonance radiation output shows that there is a possibility to increase the output by about 10% by the changing isotopes ratio. However the photochemical method of isotope separation is expensive and this task seems not essential.