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Low-Energy X-ray Dosimetry Studies (6 to 16 keV) at SSRL Beamline 1-5[1]

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Abstract. Synchrotron radiation facilities provide a unique opportunity for low-energy x-ray dosimetry studies because of the availability of monochromatic x-ray beams. Results of such studies performed at the Stanford Synchrotron Radiation Laboratory (SSRL) are described. Polish lithium fluoride thermoluminescent dosemeters (TLDs), MTS-N(LiF:Mg, Ti- 0.4 mm thick), MCP-N (LiF:Mg, Cu, P - 0.4 mm thick) were exposed free in air to monochromatic x-rays (6 -16 keV). These exposures were monitored with an SSRL ionization chamber. The responses (counts /Gy) of MTS-N and MCP-N were generally found to increase with increasing energy. The response at 16 keV is about 3 and 4 times higher than the response at 6 keV for MTS-N and MCP-N, respectively. Irradiation at 6 keV indicates a fairly linear dose response for both type of TLDs over a dose range of 0.01 to 0.4 Gy. In addition there appears to be no significant difference in responses between irradiating the TLDs from the front and the back sides. The energy response of the PTW ionization chamber type 23342 relative to the SSRL ionization chamber is within ±4.5 % between 6 and 16 keV. Both the TLDs and the PTW ionization chamber can also be used for beam dosimetry.

I. INTRODUCTION

There are currently over thirty synchrotron radiation (SR) facilities in operation around the world, with another twenty-eight in the construction, design, or proposal stage. As SR facilities are rapidly being built all over the world, they introduce the need for low-energy x-ray dosemeters because of the potential radiation exposure to experimenters who work in close proximity to the SR beamlines and experimental enclosures. However, they also are an important resource for providing monochromatic x-rays that can be used for research and calibration of dosemeters.

Most of the commercially available dosemeters are not designed to respond well to low-energy x-rays (< 30 keV) and frequently their responses at these low energies are not well known. Further, the holder or dosemeter packaging significantly attenuates the low-energy photons (< 10 keV). Hence there is a critical need to develop a low-energy x-ray dosemeter. With this as the ultimate goal, a series of studies have been undertaken at SSRL, in which the low-energy responses of both active and passive detectors such as thermoluminescent dosemeters (TLDs), are being determined using monochromatic x-rays.

In principle purely monoenergetic beams are necessary to determine the response function of any dosemeter. The availability of monochromatic x-rays at any discrete energy below 30 keV, at synchrotron radiation (SR) facilities provides unique opportunities for low-energy x-ray dosimetry studies. Calibration facilities normally make use of filtered techniques with x-ray machines that produce continuous spectra to generate "nearly" monoenergetic photon beams. These photon beams have a spectrum with a peak at the desired energy. Only a few energies in the desired energy range (<30 keV) are available.

In addition, low-energy x-ray dosemeters are useful in both radiotherapy and radiodiagnostic techniques. In radiotherapy, x-rays with energies between 5 and 20 keV are used to treat certain types of skin disorders. The spatial distribution of the dose over the treatment area can be determined with TLDs. X-rays with energies of 10 keV and above are frequently used in diagnostic medicine, for example, mammography at 17.5 keV.

In order to do accurate dosimetry, detectors that have been calibrated against primary or secondary standards are required. Since the ionization chambers that were used in the experiments at SSRL had not been calibrated against any standards, the response of the PTW ionization chamber Type 23342[2], in the energy range of 6 to 16 keV was investigated. This type of chamber is used routinely for absolute dosimetry in radiotherapy, and is also used in secondary standards laboratories.

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[2] PTW-Freiburg, Lorracher Strasse 7, D-79115 Freiburg, Germany

Thermoluminescence describes the process of emission of optical radiation from a material upon heating. When a crystal is exposed to ionizing radiation, free electrons and holes are produced. The electrons and holes may become trapped at defect sites as they migrate through the crystal. The trapped electrons will remain in their traps provided that they do not acquire sufficient energy to escape. If the temperature of the material is raised trapped electrons may acquire sufficient thermal energy to be released. The energy gap between the trap and the conduction band determines the temperature required to release the electron. Released electrons may then combine with holes at luminescent centers and the excess energy is radiated as visible or ultraviolet light. An annealing procedure is necessary for TLDs to empty all the shallow and deep traps.

The plot of light intensity as a function of temperature is referred to as a glow curve. Since there are many trapping levels present, each trapping level will give rise to an associated glow peak maximum, which may or may not be resolved during the readout. Most TLD materials have low temperature peaks (i.e., peaks occuring at temperatures lower than the main dosimetric peak). Since these peaks are not stable at room temperature and particularly below 100^{o}C their fading may impact the results of measurements. Hence, a partial annealing before the readout known as a pre-readout annealing is used to remove the low temperature peaks. Thus, both accuracy and precision of the readout is improved.

The area under the glow curve and therefore the response of the TLD is proportional to the energy absorbed in the TLD for a given type of radiation. Preliminary studies on the low-energy (7 - 17.5 keV) response of the Harshaw/Bicron LiF TLDs indicate that for thicker TLDs (> 0.2 mm), the predicted response per unit absorbed dose in air, based on energy absorbed in the TLDs is significantly greater than the measured response (1). The differences between measured and predicted responses at low energies can be attributed to the attenuation of photons and the attenuation of light in the TLD. Once the low-energy response of various TLDs is known, additional characteristics such as overall TLD efficiency, effective energy attenuation coefficient, and light attenuation coefficient can be determined as a function of energy. The effective energy attenuation coefficient can be determined from Monte Carlo simulations of energy deposition in the TLD. Using a combination of measured responses obtained by irradiating the TLDs from the front and back sides, and a theoretical TLD response model, the light attenuation coefficient and overall TLD efficiency can be determined. These parameters are vital for the understanding of basic TL mechanisms. The energy response is particularly important in assessing the potential use of different TLD materials for low-energy x-ray dosimetry.

In this paper we report the results of experiments to determine the low-energy (6-16 keV) response of the Polish TLDs (MCP-N, MTS-N), and the PTW ionization chamber.

II. THEORETICAL MODEL FOR RESPONSE OF TLD

It can be shown that the responses R(k) and R'(k) of the TLD when read with the irradiated side facing the photomultiplier (PM) tube and away from the PM tube, respectively, are given by equations 1 and 2 (Appendix A).

$$R(k) = \frac{CN\mu(k)k}{\mu(k)+f}\left\{1 - e^{-[\mu(k)+f]t}\right\} \tag{1}$$

$$R'(k) = \frac{C'N\mu(k)k}{\mu(k)-f}e^{-ft}\left\{1 - e^{-[\mu(k)-f]t}\right\} \tag{2}$$

where:

R(k) = TLD response for N photons each of energy k when read with irradiated side facing PM tube
R'(k) = TLD response when read with irradiated side away from PM tube
C = $\eta\varepsilon$ = Overall TLD efficiency when read with irradiated side facing PM tube
C' = Overall TLD efficiency when read with irradiated side away from PM tube
η = Intrinsic luminous efficiency
ε = Reader efficiency
$\mu(k)$ = Effective energy attenuation coefficient
f = Effective light attenuation coefficient
t = TLD thickness

Dividing equation 1 by equation 2 and assuming C = C' we obtain equation 3:

$$\frac{R'(k)}{R(k)} = \frac{e^{-ft}\left\{1 - e^{-[\mu(k)-f]t}\right\}(\mu(k)+f)}{\left\{1 - e^{-[\mu(k)+f]t}\right\}(\mu(k)-f)} \tag{3}$$

$\mu(k)$ can be determined from Monte Carlo simulations of energy deposition studies in the TLD. Once $\mu(k)$ is known, f can be determined numerically from equation 3. Using $\mu(k)$ and f in equation 1, C can be determined. Energy deposition studies in the Polish TLDs, MCP-N (^{nat}LiF: Mg, Cu, P) and MTS-N (^{nat}LiF: Mg, Ti) were performed using FLUKA (2), a Monte Carlo code. The energy deposited in thin layers, each of thickness about 0.1 mm and radius 2.25 mm was scored in ~5 cm-thick disks of MCP-N and MTS-N TLDs for photon energies of 7, 9, 12 and 15 keV. $\mu(k)$ was obtained from the energy vs depth in TLD curves. Table 1 lists the effective energy attenuation coefficients obtained from FLUKA and the theoretical energy absorption coefficients (provided by the manufacturer) of both MCP-N and MTS-N. The errors on the FLUKA values are about 0.2%. Thus it can be seen that the effective energy attenuation coefficient is the same as the energy absorption coefficient. The differences (up to 10%) can be attributed to the different cross sections used in the theoretical and FLUKA calculations.

TABLE 1. Energy Attenuation Coefficients For TLD's

Energy (keV)	**Energy Attenuation Coefficient (cm^{-1})**			
	MTS-N		**MCP-N**	
	FLUKA	**Theoretical**	**FLUKA**	**Theoretical**
7	43.29	44.25	47.47	48.00
9	20.25	20.90	22.87	23.45
12	8.42	8.99	9.45	10.13
15	4.27	4.71	4.86	5.32

III. EXPERIMENTAL CONDITIONS

Experiments were performed at the Stanford Synchrotron Radiation Laboratory (SSRL) Beamline 1-5 using synchrotron radiation from the 3 GeV electron storage ring SPEAR (a schematic of the beamline is shown in Fig. 1). The experimental layout is described in detail in Reference 1. The synchrotron radiation enters the beamline through a pair of beryllium windows, a pair of vertical slits and a pair of horizontal slits. The beam is then incident on a downward reflecting monochromator comprised of 2 silicon (111) crystals. A white beam stop in the monochromator ensures that white light does not enter the downstream experimental enclosure. A piezoelectric crystal adjustment is used to detune the monochromators to eliminate the higher energy harmonics. The x-ray beam is then transported into the experimental enclosures (not shown in the figure).

Two parallel-plate ionization chambers are mounted downstream of the mono beam shutters. The portion of the beam line downstream of the mono shutters is mounted on a motorized table that is capable of both horizontal and vertical motion. A shutter and a series of filters are mounted in a holder between the ionization chambers. The shutter regulates the x-ray dose to the sample. The filters are used to calibrate the energy of the mono beam by scanning across an absorption edge, while measuring the beam intensity with the ionization chambers both before and after the filter. The ionization chambers are operated at a high voltage of 310 volts and are filled with slowly flowing nitrogen at atmospheric pressure. A set of horizontal and vertical Huber slits define the beam size at the dosemeter position.. A third ionization chamber placed downstream of the manual slits is used to monitor the dose to the dosemeters or detectors. A collimator after the third ionization chamber acts as a guard slit. Dosemeters were mounted in specially designed plexiglass holders. The entire system is under the control of a computer that drives the monochromator to the desired energy and exposes the sample to the selected radiation dose.

The lithium fluoride Polish TLDs obtained from the Institute of Nuclear Physics, Poland, were MCP-N- 0.4 mm thick (3) and MTS-N -0.4 mm thick. The TLDs are solid circular sintered pellets of diameter 4.5 mm. According to the manufacturer, the detection threshold is about 10000 and 50 nGy, respectively and the response is linear between $5x10^{-5}$ and 3, and 10^{-7} and 10 Gy, respectively. The photon energy dependence is within 30 and 20 % , respectively between 30 keV and 1.3 MeV. The thermal fading at room temperature is about 5% per year for both types of TLDs and the fluorescent light effect on fading and zero reading is negligible.

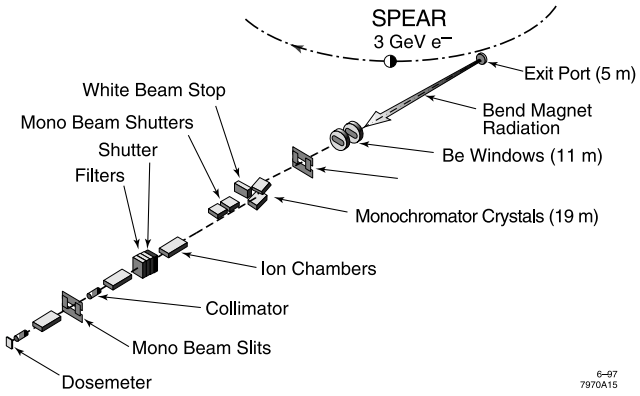

FIGURE 1. Schematic of SSRL Synchrotron Radiation Beam Line 1-5.

The TLDs were read out at the Institute of Nuclear Physics using an RA '94*[3] reader equipped with a photomultiplier tube (EMI 9789QB) with a bialkali photocathode and BG-12 optical filter. The pre-readout annealing consists of heating the dosemeters at 100 ^{o}C for 10 minutes.

The readout cycle consists of a linear ramp at 5 ^{o}C/s. The maximum temperature is typically 350 ^{o}C for MTS-N and 280^{o}C for MCP-N. The annealing cycle is as follows:

MTS-N - 400 ^{o}C for 1 hour and 100 ^{o}C for 2 hours.

MCP-N - 240 ^{o}C for 10 min followed by fast cooling on an aluminum plate.

The "GaFChromic^{TM} Dosimetry Media" film MD-55 is a radiochromic film which was used for imaging because of its high spatial resolution (4). It is colorless before irradiation and turns progressively blue with increasing absorbed dose.

The PTW ionization chamber type 23342 consists of a rectangular block 61 mm in length, 22m in width, and 14.4 mm in height. The cylindrical air-filled cavity inside has a diameter of 5.2 mm and is covered by a thin membrane window. The sensitive measuring volume is defined by the electrode which has a diameter of 3 mm and the distance (1mm) between the two electrodes. Additional information regarding the chamber can be obtained from the instrument manual available from the manufacturer. The chamber was connected to a Keithley electrometer 602. A variable battery source was used for voltage supply. The GaFChromic film was used to center the beam on the window. According to the manufacturer, the energy dependence of the chamber is within ±2 % in the energy range of 20 keV to 70 keV. The chamber is open to air and hence requires a temperature correction. At an operating voltage of 300 volts the chamber collects more than 99.5% of all the charges produced by continuous radiation with dose rates of up to 175 Gy/s and pulsed radiation with pulsed dose rates of up to 1.8 mGy/s.

IV. EXPERIMENTAL PROCEDURE

The horizontal and vertical slits upstream of the third ionization chamber were adjusted so that the beam size at the sample position was 1.4 mm × 1.4 mm. This was verified by measuring the size of the beam on the GaFChromic film with a microscope. The monochromator was calibrated using an iron filter. The monochromator was then set at various energies ranging from 6 to 16 keV. At each energy, the harmonics were monitored by studying the energy spectrum scattered by a thin capillary tube using a Bicron sodium iodide (NaI) scintillator (Model 1XMP040B-X)[4]. The NaI scintillator was mounted vertically at 90° to the incident beam direction and connected to a Trump 8K/2K multichannel analyzer (MCA). The scintillator/MCA was calibrated using a ^{241}Am source with various filters (Cu, Mo, Ba, Rb, Tb, Ag, Fe). The monochromator was detuned so that the intensity of the mono beam was reduced by 20%. Spectral measurements confirmed that this amount of detuning was sufficient to eliminate completely the higher harmonics at each energy (the harmonics were most significant at energies between 6 and 8 keV). At each energy the beam was centered on the dosemeter, by adjusting the beamline so that the current in the ionization chamber that monitors the dose to the sample was maximized. The GaFChromic film was used to obtain an image of the beam at each energy.

The dosemeters were mounted in specially designed sample holders. The temperature, pressure and ionization chamber integrated currents were noted at each irradiation. The ionization chamber readings were converted to dose in air and corrected for attenuation in the nitrogen and air paths to obtain the dose in air at the sample position. At each energy, 6 TLDs were exposed to doses varying from 0.01 to 0.03 Gy with the front (numbered) side facing the beam, and 6 with the

[3] Mikrolab, Krakow, Poland

[4] Harshaw/Bicron, 6753-I Cochran Road, Solon, Ohio 44139

front side away from the beam. The TLDs were also exposed to integrated doses varying from about 0.01 to 0.4 Gy at 6 keV. Sixteen TLDs were used as controls.

The PTW ionization chamber was exposed at each energy and the dose rate was corrected for temperature and pressure. The ionization chamber was operated at a voltage of 280 V.

V. RESULTS AND DISCUSSION

Figure 2 shows the response (response per unit absorbed dose in air at the dosemeter location) in counts/Gy for the MTS-N and MCP-N TLDs as a function of energy for integrated doses of about 0.01 to 0.03 Gy for a beam size of 1.4 mm x 1.4 mm. The average responses are shown. The error bars are smaller than the size of the symbols. The open and closed symbols represent the data for TLDs with beam incident on the front and back surfaces, respectively. The response of the TLDs to Cs-137 is also shown.

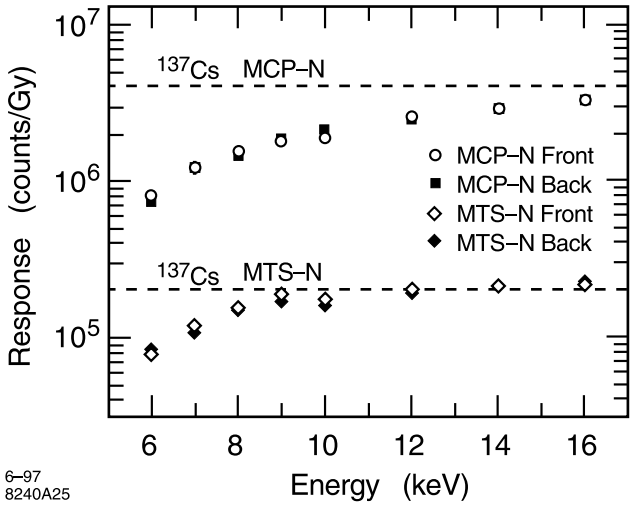

FIGURE 2. Response of Polish TLDs as a Function of Energy (0.01- 0.03 Gy)

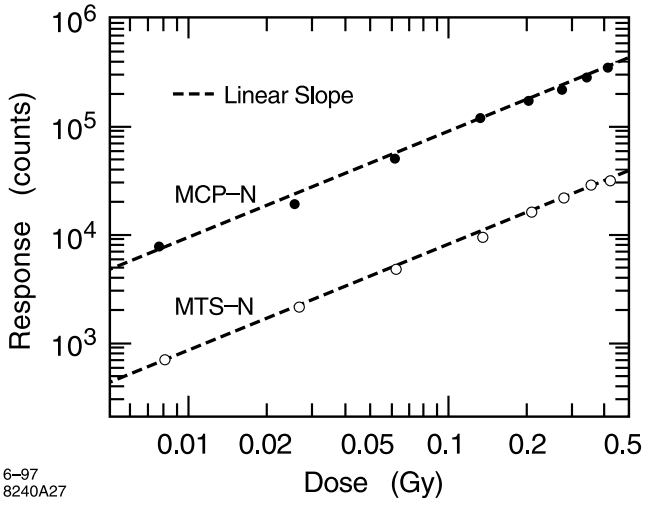

FIGURE 3. Response of Polish TLDs as a Function of Dose at 6 keV

The responses of both MTS-N and MCP-N increase with increasing energy. No differences in the shape of the glow curves were observed for x-ray energies between 6 and 16 keV. The responses of MTS-N and MCP-N at 16 keV are about 3 and 4 times higher than the response at 6 keV, respectively.

The response of MCP-N is about 10 to 15 times higher than the response of MTS-N at the low energies. For both TLD types the difference between the front and back irradiations is within the variability between the dosemeter. Hence, it was not possible to determine the light attenuation coefficient as we had hoped to. The differences in response between front and back irradiations may be more significant in thicker TLDs. This will be the thrust of future studies.

Figure 3 shows the response (counts) as a function of absorbed dose in air for 6 keV x-rays, for both MTS-N and MCP-N. The response is fairly linear over the dose range shown. Future studies will include the dose response over a wider range of doses, and at several energies.

Figure 4 shows the response of the PTW ionization chamber relative to the SSRL ionization chamber as a function of energy. The energy response of the PTW ionization chamber is within ±4.5 % between 6 and 16 keV for dose rates varying between 0.03 and 0.3 Gy/s.

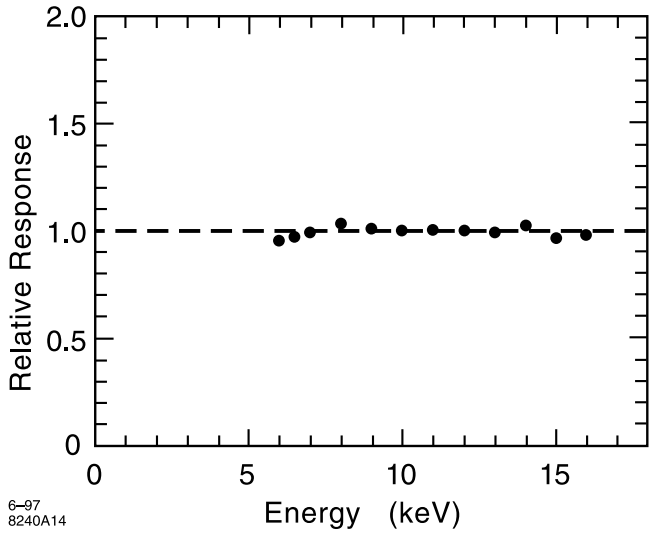

FIGURE 4. Response of PTW Ionization Chamber Relative to SSRL Ionization Chamber vs Energy

VI. CONCLUSIONS

The need for low-energy x-ray dosemeters has increased because of the increasing number of synchrotron radiation facilities being built around the world. The SSRL Beamline 1-5 was used for low-energy x-ray dosimetry studies (6 to 16 keV).

The measured responses of the Polish TLDs were found to increase between 6 and 16 keV, with the response of MCP-N being 10 times higher than that of MTS-N. The response at 16 keV is 3 and 4 times higher than the response at 6 keV for MTS-N, and MCP-N, respectively. The differences between irradiating the TLDs from the front and back is within the variability between the TLDs. Future studies will include the response of thicker TLDs, as well as the dose response over a greater range of doses at each energy.

The energy response of the PTW ionization chamber is within ±4.5 % between 6 and 16 keV. It is therefore suitable for low energy x-ray dose rate measurements. Both the TLDs and the PTW ionization chamber can be also be used for beam dosimetry.

VI. APPENDIX A

Proposed Model for Response of TLD

Under “ideal” narrow beam conditions, exponential attenuation (described by a linear attenuation coefficient μ) will be observed for a monoenergetic beam of photons incident on a material. The photons are “ideal” in the sense that they are absorbed without producing scattered or secondary radiation. Real photon beams interact with matter producing both

secondary and scattered radiation. Monte Carlo simulations show that the energy deposited per unit thickness, dE/dx, is exponentially distributed in the TLD along the beam direction x:

$$\frac{dE(k)}{dx} = N\mu(k)ke^{-\mu(k)x} \tag{1}$$

where N is the number of incident photons, μ(k) is an effective energy attenuation coefficient and k is the photon beam energy.

Assuming a simple exponential model also for light absorption (ignoring reflection of light from the planchet) an elemental layer of thickness dx, located at a distance x from the face of the TLD, will contribute an amount dR to the response R. dR is proportional to the energy dE = (dE/dx)dx deposited in that layer, weighted by a light absorption factor e^{-fx} and is given by :

$$dR(k) = C\frac{dE(k)}{dx}e^{-fx}dx \tag{2}$$

where C=ηε is the overall TLD efficiency, η is the intrinsic luminous efficiency, ε is the reader efficiency and includes geometry dependence, sensitivity of the photomulitplier (PM) tube, etc. and f is the effective light attenuation coefficient of the TLD material.

Combining equations 1) and 2), we obtain:

$$dR(k) = CN\mu(k)ke^{-[\mu(k)+f]x} \tag{3}$$

if the TLD is read out with the irradiated side facing the PM tube.

Equation 4) is obtained by integrating the response over the whole TLD thickness t:

$$R(k) = \frac{CN\mu(k)k}{\mu(k)+f}\left\{1-e^{-[\mu(k)+f]t}\right\} \tag{4}$$

In a similar way, we can obtain equation 5) for the case in which the detector is read out with the irradiated side facing away from the PM tube:

$$dR'(k) = C'N\mu(k)ke^{-[\mu(k)x-f(t-x)]}dx \tag{5}$$

where C' is the overall TLD efficiency when the TLD is read out with the irradiated side facing away from the PM tube. Integration of equation (5) results in equation 6):

$$R'(k) = \frac{C'N\mu(k)ke^{-ft}}{\mu(k)-f}\left\{1-e^{-[\mu(k)-f]t}\right\} \tag{6}$$

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