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Worldwide Status of Personnel Monitoring using Thermoluminescent (TL), Optically Stimulated Luminescent (OSL) and Radiophotoluminescent (RPL) Dosimeters

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Abstract:
As per the UNSCEAR 2008 Report, about 23 million workers globally are monitored and these workers receive an annual collective dose of ~ 42000 man Sv. This collective dose is dominated by doses of the 13 million workers in industries with enhanced exposure to natural sources (e.g. mining and other industries with enhanced exposure to radon). For artificial (man-made) sources of radiation, the medical sector dominates the global occupational collective dose. Thus, about 10 million workers are exposed to radiation from artificial sources, which include medical uses sector, nuclear fuel cycle, industrial uses, miscellaneous uses and military activities. External monitoring of these radiation workers is carried out using personnel dosimetry badges, which include thermoluminescent dosimeters (TLDs), optically stimulated luminescent dosimeters (OSLDs), radio-photoluminescent dosimeters (RPLDs) and film badges. In the mid 1950s, it was standard practice to wear a film badge with a number of filters as well as pocket ionization chambers for routine day-to-day monitoring. TLD personnel monitoring systems were introduced in late 1960s and during 1970s. In the next two decades tremendous development took place in the field of TL personnel dosimetry worldwide. Many fully automatic personnel monitoring systems were introduced for monitoring of radiation workers during this period. However, thrust of modern luminescent dosimetry development is more towards optically stimulated luminescence, as all-optical nature of OSL readout does not require heating of the detector and thus, removes completely the problems of thermal quenching associated in TL mode of readout in some of the phosphors. Use of OSL as personnel dosimetry technique started in mid 1990s, with the development of Al_2O_3:C by Akselrod et al. in 1990 and later investigation of its suitability for personnel dosimetry using pulsed-OSL (POSL) for stimulation by Akslerod and McKeever in 1999. Since then OSL dosimeters are finding more and more applications in the field of personnel and environmental monitoring as well as in the field of medical physics. Another important optically stimulated dosimetry system is the radiophotoluminescent (RPL) glass dosimeters. Fully automatic RPL dosimetry systems capable of measuring doses in the range 10μSv to 10Sv were developed in1980s. In 2001 silver activated phosphate RPL glass dosimetry system has been introduced as the major personnel monitoring service in Japan marketed by Chiyoda Technol Corporation. This paper will endeavor to highlight some of these developments in the field of external personnel dosimetry.

1 INTRODUCTION

The primary objective of personnel monitoring/individual monitoring is the measurement or assessment of radiation dose delivered to personnel during their occupational exposure (ICRP-60, 1991). Examples include workers in nuclear industry, hospital radiotherapy technicians, workers in industrial radiography and high intensity gamma irradiators and naval personnel on nuclear powered vessels. Personnel monitoring results provide information on routine radiation exposures, assist in work planning, allow control of the workplace, and provide exposure information in accident situations. In addition, these results assist those responsible for radiation safety in keeping exposures as low as reasonably achievable (ALARA). Finally, personnel monitoring is mandatory activity as it is required by the relevant national radiation regulations.

Although it is not exactly known when organized personnel monitoring (PM) actually began, it is stated that certainly the Manhatten project provided a major impetus for monitoring of all types, including personnel monitoring [1]. Photographic film-based personnel dosimetry systems were introduced somewhere in late 1943. In the mid 1950s, it was standard practice to wear a film badge with a number of filters as well as pocket ionization chambers for routine day-to-day monitoring. Fully automatic film-based systems were operational in the 1960s. TLD personnel monitoring systems were introduced in late 1960s and during 1970s. In the next

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three decades tremendous development took place worldwide in the field of TL personnel dosimetry. Many fully automatic personnel monitoring systems were introduced for monitoring of radiation workers during this period. At the same time many film-based systems were replaced by TLD-based personnel monitoring systems as these were established to be superior to film-based system in their performance through repeated intercomparison exercises. During 1980s and 1990s, many TLD based commercial PM systems were introduced for monitoring of radiation workers.

Thrust of modern luminescent dosimetry development is more towards optically stimulated luminescence, as all-optical nature of OSL readout does not require heating of the detector and thus, removes completely the problems of thermal quenching. The development of Al_2O_3:C was reported by Akselrod et al.[2] in 1990 and later investigation of its suitability for personnel dosimetry using pulsed OSL (POSL) technique for stimulation by Akslerod and McKeever in 1999 [3], led to the development of Landauer's Luxel™ personnel dosimetry system based on Al_2O_3:C OSL phosphor in late 1990s. Since then OSL dosimeters are finding more and more applications in the field of personnel and environmental monitoring as well as in the field of medical physics [4]. The main advantages of OSL techniques are: (i)Sample heating is not required which also means that problems due to thermal quenching are removed, (ii) Optical nature of readout process also allows the use of low melting point dosimeter materials, namely, luminescence phosphors impregnated into a plastic matrix. Thus, robust dosimeters may be manufactured, (iii) The high sensitivity of OSL in some phosphors, such as Al_2O_3:C, also leads to advantages related to multiple readings (using POSL mode of readout) since it is often not necessary to stimulate all the trapped charge in order to read a sufficient luminescence signal, and readout process can be made very fast (<1s) through adjustment of the stimulating light intensity leading to advantages associated with the rapid analysis of large number of dosimeters.

Another important optically stimulated luminescence dosimetry system is the radiophotoluminescent (RPL) glass dosimeters. In mid 1980s development of improved RPL glass dosimeters as well as introduction of improved readout systems using a pulsed UV laser excitation in place of conventional mercury UV lamps, helped in reducing pre-dose by a factor of 100 (from mSv to a few μSv). This development resulted in the manufacture of improved RPL glass dosimeters and fully automatic RPL reader systems capable of measuring doses in the range 10 μSv-10Sv. In 2001 silver activated phosphate RPL glass dosimetry system has been introduced as the major personnel monitoring service in Japan marketed by Chiyoda Technol Corporation [5].

Worldwide Status of Personnel Monitoring

As per UNSCEAR 2008 Report [6,7], about 10 million workers are exposed to radiation from artificial sources, which include medical uses sector, nuclear fuel cycle, industrial uses, miscellaneous uses and military activities. External monitoring these radiation workers is carried out using personnel dosimetry badges, which include thermoluminescent dosimeters (TLDs), optically stimulated luminescent dosimeters (OSLDs), radio-photoluminescent dosimeters (RPLDs) and film badges. As per the earlier information in the book of Botter-Jensen et al. [4] there were about five million personnel dosimetry badges being used by radiation workers around the world, including: thermoluminescence dosimeters (TLDs), film badges, optical stimulated luminescence (OSL) dosimeters and radiophotoluminescence (RPL) dosimeters. Over 1.6 million badges are OSL dosimeters, primarily based on Al_2O_3:C based OSL dosimetry systems marketed by Landauer Inc. [8]. IBA OSL personnel dosimetry system based on BeO sintered chips, has been introduced recently, which is reported to be fully operational [9,10]. About 4,20,000 of the total badges are RPL glass dosimeters, primarily based on relatively low-Z silver-activated phosphate glass dosimeters using the commercial system marketed by Chiyoda Technol Corporation, Japan[5,11]. The remaining are TLDs and film dosimeters. Table 1 gives different personnel monitoring systems being used for individual monitoring of radiation workers. It could be seen from the table that at present TL dosimetry systems are major players in personnel dosimetry arena; OSL systems are the second largest dosimetry systems. Comparative advantages of TL , OSL and RPL dosimeters are given in a recent paper [12].

There is a large number of TL dosimetry systems used for individual monitoring in Europe. Olko et al.[13,14] had collected information about TL dosimeters (TLDs) applied by the European dosimetric services through EURODOS (European Dosimetry Group) questionnaire distributed among dosimetric services in the European Union (EU) candidate countries and other European countries. As per the information collected through the questionnaire, total number of services in the European Union and Switzerland were estimated to be about 200 [14]. Most individual dosimetric services in Europe using dosimeters based on TLDs are small and medium size services, which operate typically for >10,000 radiation workers. Among 91 services from 29 countries, which responded to the EURADOS questionnaire between 1997 and 2003: 61 services apply dosimeters with TLDs for the determination of personal dose equivalent $H_p(d)$ for photons and beta radiation, and 16 services use TLDs for neutron albedo dosimeters. The other services were applying dosimeters based on dosimetric films, track etched detectors and radiophotoluminescent detectors. More than two-third of the services were using lithium fluoride LiF:Mg,Ti detectors (mainly TLD-100, TLD-700, MTS-N and MTS-7) read in Harshaw/ThermoElectron and RADOS/Dosacus TL readers. The other most frequently applied detectors are $Li_2B_4O_7$:Cu and $CaSO_4$:Tm (used with Panasonic system), LiF:Mg,Cu,P and $Li_2B_4O_7$:Mn,Si. In neutron albedo dosimetry, pairs of TLDs with different sensitivity to thermal neutrons are applied, exploiting enhanced cross section for (n,α) reactions with ^{6}Li or ^{10}B. Among 25 services, which provided neutron dosimetry service, 16 were applying pairs of ^{7}LiF/^{6}LiF detectors, mainly TLD-700/TLD-600 and MTS-7/MTS-6. Among the 31200 radiation workers monitored with individual neutron dosemeters, 20,000 workers were usually from the nuclear industry. Energy response of albedo dosemeters is poor for energies above a few MeV and cannot be applied for higher neutron energies, e.g. around high-energy accelerators [13,14].

There are about 35 laboratories/dosimetry service providers, accredited by National Voluntary Laboratory Accreditation Program (NVLAP, NIST, USA), who provide personnel dosimetry services to users of radioisotopes and/or radiation in USA [15]. Such processors provide personnel dosimetry services in many other countries.

Table 1. Different personnel monitoring systems being used for individual monitoring of radiation workers.

System	Dosimeter
Harshaw TLD Badge (Thermo Electron Corp., USA)	LiF:Mg,Cu,P or LiF:Mg,Ti All around the world
Many other LiF based commercial systems in Europe.	MCP-N (LiF:Mg, Cu,P Poland) MTS-N (LiF: Mg, Ti Poland) GR-200 (LiF:Mg, Cu,P China) DTG-4 LiF:Mg, Ti Russia) All around the world
Teledyne Isotopes, USA	$CaSO_4$:Dy Teflon Tape Card a) Korea, b) Some Labs in USA
TLD badge system based on $CaSO_4$:Dy Teflon discs	a) India, b) Australia
Panasonic TLD Badge (Japan)	$Li_2B_4O_7$:Cu & $CaSO_4$:Tm In many countries.
RADOS, Finland	$Li_2B_4O_7$:Mn, Si
Vinca, Serbia and Montenegro	$Li_2B_4O_7$:Cu, Ag, P; MgB_4O_7:Dy, Na
Landauer Inc., USA	Al_2O_3:C OSL badge All around the world.
IBA OSL Personnel Dosimetry System	BeO sintered chips Germany.
Chiyoda Technol Corporation, Japan	Silver-activated phosphate glass dosimetry system (in Japan, France, Germany, etc.)

In Germany there are different dosimeters in use: (i) For whole body measurements: film-badges, TL-dosimeters for photons and neutrons (albedo), and OSL-dosimeters. (ii) For extremity different ring-dosimeters (TLD) are used. Four accredited monitoring services, in Germany, which provide individual monitoring to about 330.000 radiation workers [10]. In Brazil[16], all workers (120,000) occupationally exposed to ionizing radiation must use an individual monitor obtained from authorized External Individual Monitoring Services (IMS), according to norms and national regulations, using Harshaw LiF:Mg,Cu,P chips , finger rings (for extremity monitoring) and film dosimeters (for 6000 radiation workers).

The dosimeters in use in UK include Film, Thermoluminescent Dosimeters (TLD), Optically Stimulated Luminescence (OSL), "Passive" Ion storage, and "Active" Electronic (EPD). Other methods used include whole body monitoring and internal dosimetry. A Biological monitoring service is provided by the UK Health Protection Agency which includes chromosome aberration analysis but this is not currently subject to approval. There are approximately 250,000 UK workers monitored and of these around 30,000 are classified radiation workers (i.e. those likely to exceed 3/10's of a dose limit, subject to medical surveillance and dose record keeping under the UK regulations/European

Directive. There are approximately thirty different companies that are approved by Health and Safety Executive (HSE), UK for dosimetry services [17]

In India, since 2003 all the radiation workers (presently, about 90,000) are monitored using a $CaSO_4$:Dy embedded TLD disc based personnel monitoring badge system. Among these about 60 % of the radiation workers are provided dosimetry services by the three accredited laboratories. The dosimetry system used by these accredited laboratories complies with the requirements of International Electrotechnical Commission for Thermoluminecence Dosimetry systems for Personnel Monitoring as well as the quality assurance procedures for personnel dosimeters. Also, two laboratories of the government institutions – Defence Laboratory, Jodhpur (DLJ) and IGCAR, Kalpakkam, DAE – have been accredited for carrying out personnel monitoring of radiation workers in the respective institutions. Recently, seven Dosimetry Laboratories of Nuclear Power Corporation India Ltd.(NPCIL) have been accredited for carrying out personnel monitoring of radiation workers working in nuclear power reactors of NPCIL. With this there are now 12 accredited TLD Laboratories who provide personnel monitoring service to radiation workers in India, except the radiation workers of BARC facilities, who are covered by the TLD Monitoring Laboratories of BARC [18].

2.1 OSL PERSONNEL DOSIMETRY SYSTEM

2.1.1 Landauer's Luxel™ Personal Dosimetry System

The OSL badge, i.e., the detector, is a thin layer of Al_20_3:C powder deposited onto a clear polyester film base. The size of the active area of the detector is 16.5 mm by 18.5 mm and the grain size of the Al_2O_3:C powder is in the range 20-90 μm. The powder layer is protected by a thin, clear polyester tape. A typical POSL measurement takes 350-1000 ms per reading, and each reading depletes the POSL signal by only a fraction of the stored information available. Thus, second, third, or more readings may be performed if required, in order to achieve true second dose readings from one dosimeter.

2.1.2 Landauer's InLight™ Personal Dosimetry System

Later, InLight™ personal dosimetry system was also developed by Landauer. This is a bench-top, CW-OSL system specifically designed for personal dosimetry and uses bright LEDs (green) to stimulate the OSL. It is again based on Al_2O_3:C. The use of LEDs results in longer readout times compared with POSL, but enables dose readings for very little depletion of the signal.

2.1.3. IBA Personnel Dosimetry System based on BeO Sintered Chips

The IBA personnel dosimetry system based on BeO sintered chips, is now fully operational. There are two bigger systems installed and operational. One is operated by AV-Controlatom in Belgium since 2010, using a 4-element dosimeter badge. The second system runs since 2011 at Helmholtz Zentrum Muenchen, Germany using a 2-element dosimeter badge. The dosimeter is type tested by the PTB, Germany and applies to the IEC 62387 standard [10].

2.2 RPL Glass based Personnel Dosimetry

In 2001, silver-activated phosphate RPL glass dosimetry has been introduced as the major personnel monitoring service in Japan. The RPL glass dosimetry badge system has been designed to measure 10 keV to 10 MeV range of protons, 300 keV to 3 MeV range of beta radiations. ADC plastic solid state nuclear track detector (SSNTD), which is loaded to RPL glass badge, is incorporated for neutron monitoring in wide energy range. SSNTD has two types of charged particle radiator – BN (Boron nitride) and Polyethylene to cover wide energy range (0.025 eV to 15 MeV) of neutron dose measurement. Detectable dose limit for the RPL glass is 14 μSv (0.014 mSv) for ^{137}Cs gamma rays. About 2,70,000 glass dosimeters are processed every month at Radiation Monitoring Center (RMC) in Oarai, Ibaraki, Japan. The Glass Dosimetry system (GD-450 glass dosimeter and FDG-650 automatic reader) is capable of processing 2000 dosimeters in less than 7 hours with a readout time of 12 seconds per dosimeter. In 2007, IRSN in France has purchased the automatic Glass Dosimetry System of Chiyoda Technol Corporation for replacing the photographic film based monitoring of about 1,50,000 radiation workers.

Workplace Monitoring

Workplace monitoring includes measurement of radioactivity on surfaces and in the air as well as radiation field analysis. These methods normally complement individual monitoring. In some cases the resulting dose is not individually measured but derived from workplace monitoring methods. For a large number of persons occupationally exposed to naturally occurring radioactive material, no individual monitoring is in place and the occupational dose can be estimated on workplace monitoring data only.

Performance requirements of Personnel Dosimetry Systems

In a controlled, laboratory-exposure situation, most personnel dosimeters show an accuracy in the range of ±3-5% (1σ). However, when the badges are worn by workers in an uncertain exposure situation (with scattered radiation fields, shielding of the wearer's body, variable angles of incidence on the dosimeter, and many other factors), the acceptance of more realistic accuracies must be understood [1].

The accuracy of personnel monitoring data varies depending on the level of exposure [1,19]. In general, at routine levels currently encountered in most workplaces, the dosimeter can have accuracy on the order of -50% and +100%, at the 95% confidence level (for doses typically in the range of one-fifth of the dose limit). However, as the doses increase the acceptable accuracy decreases, reaching -33% and +50% at the 95% confidence level near the legal dose limit. Finally, the accuracy should be about ±25% as the doses approach those in the life-threatening range, i.e. greater than 1000 mSv.

3. CONCLUDING REMARKS

Due to non-reliability of photographic film for long-term stability of stored information, this method of personnel dosimetry has nearly phased out and replaced by TL, OSL and RPL methods of personnel dosimetry. Presently, although TL is a major player in the personnel dosimetry arena, OSL technique is becoming more and more popular for various applications in radiation dosimetry. Commercial OSL personnel dosimetry system was introduced in the year 1998. OSL based dosimetry systems can serve as potential alternative to the TL based dosimetry systems. Due to availability of relatively low-Z, high-sensitivity RPL glass dosimeters and associated fully automatic RPL readout system, as well as having all good aspects as those for OSL dosimeters, popularity of RPL dosimeters is also expected to increase in future.

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