CHAPTER IX

TEHRNOLUMINESCENCE AND ITS APPLICATIONS
Thermoluminescence (TL) is known to have been first observed by Robert Boyle in 1669 (1). He reported to the Royal Society in London about a feeble light emitted by a diamond piece when it is warmed in dark. Much work was not done on the TL phenomenon or its applications for quite long time later. It is only during the last two decades that the progress in TL research and its applications has moved up phenomenally (2-5).

Presently, as an experimental technique, thermoluminescence finds favour in such diverse scientific disciplines as archaeology, geology, medicine, solid state physics, biology, organic chemistry etc. In short, by now it is established as multi-disciplinary field. As the TL characteristics of a material relate directly to the material's solid state properties and such solid state properties are being utilized in the diverse fields mentioned above; it enjoys widespread popularity, displaying enormous versatility and well used experimental method (6). Probably it is the most direct evidence we have for the existence of electronic trap levels in materials exhibiting TL. TSL is observed in a wide variety of materials (7). To investigate and understand the phenomenon it is essential to be familiar with the basic terminology used in what follows the discussion is given hereafter.
[A] LUMINESCENCE:
When radiation is incident on a material, some of its energy may be absorbed and reemitted as a light of a longer wavelength. This process is different than the Raman and Compton effects as they are completed in a time of about $10^{-8}$ sec. or less compared to time delay of $10^{-14}$ sec. or more in such cases.

[B] FLUORESCENCE AND PHOSPHORESCENCE:
The emission of light takes place within a characteristic time $T_c$, after the absorption of the radiation; on the basis of $T_c$ luminescence can subclassify as follows; Fluorescence is the reemission of energy from the material within time $T_c < 10^{-8}$ sec., say during the excitation of phosphors, whereas Phosphorescence is the light emission from the Phosphors after the cessation of the radiation source (i.e. $T_c > 10^{-8}$ sec.) In case of Fluorescence emission the spontaneous emission is exhibited within 10 sec. after stopping of incident excitation. It has life time of $10^{-7}$ to $10^{-10}$ sec. In Fluorescence the delay time is temperature independent, whereas in Phosphorescence the delay time is strongly temperature dependent. If the decay time $T_c$ is of the order of 1 sec., it is easy to classify the emission as Phosphorescence. However, for delays of a much shorter time, it is more difficult to distinguish between Fluorescence and Phosphorescence.

It is known that the mean life time, $T$ is exponentially
dependent upon temperature. For Phosphorescence, $T$ is very small and luminescence is observed easily at the temperature $T_0$, at which the irradiation takes place. However, if the trap is deep enough, then the values of $T$ go very high, in turn, the electrons will remain trapped in metastable level, indefinitely or the rate of release of trapped electrons $\frac{dn}{dt} = -\frac{n}{T}$ is very small at $T_0$. Practically, from such trap at $T_0 = 298\,\text{K}$ or less luminescence would never be observed.

However, the luminescence emission could be induced by raising the temperature. Increasing the temperature, $I(t) = -\frac{n}{T}$ becomes large enough for the luminescence to be observed. It means that raising the temperature of excited specimen; the rate of depopulation of the trapped carriers increase, in turn, their life time decreases and as a result of that stimulated luminescence is exhibited. This additional stimulating energy source could be in other form also e.g. Laser.
### THE FAMILY TREE OF LUMINESCENCE

<table>
<thead>
<tr>
<th>Luminescence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescence</td>
</tr>
<tr>
<td>-8 Tc &lt; 10 sec.</td>
</tr>
<tr>
<td>Phosphorescence</td>
</tr>
<tr>
<td>-8 Tc &gt; 10 sec.</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Short Period</th>
<th>Long Period</th>
</tr>
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<tr>
<td>-4 Tc &lt; 10 sec.</td>
<td>-4 Tc &gt; 10 sec</td>
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Thermoluminescence
or
Thermally Stimulated Luminescence
Minutes < Tc < 4.6*10 years

### TYPES OF LUMINESCENCE:

The various luminescence phenomena are termed on the basis of their modes of excitation. This excitation may be achieved by means of either electromagnetic or some ionizing radiation. Different types of luminescence processes are classified as follows: [Table I]
### Table: I Types of Luminescence

<table>
<thead>
<tr>
<th>Process</th>
<th>Exciting mode</th>
<th>Obtained by</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Photo luminescence</td>
<td>Light (UV)</td>
<td>Electromagnetic radiation source</td>
</tr>
<tr>
<td>2. Cathode luminescence</td>
<td>Electrons</td>
<td>Electron gun</td>
</tr>
<tr>
<td>3. Radioluminescence</td>
<td>X-rays, (\gamma)-rays, (\beta)-rays, Protons, Neutrons, Fissia Fragment etc.</td>
<td>Radio Isotope or Irradiation Source</td>
</tr>
<tr>
<td>5. Triboluminescence</td>
<td>Mechanical/ Frictional forces</td>
<td>External Stresses.</td>
</tr>
<tr>
<td>6. Chemiluminescence</td>
<td>Chemical reactions</td>
<td>Chemical reactions</td>
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For Radio thermoluminescence (RTL), heating though is not exciting mode rather a stimulating cause to this extent, the term is rather misnamer.
TL is the emission of light from the pre-excited insulator or semiconductor when it is heated. This thermally stimulated luminescence (TSL) emission is observed during controlled heating (scan) of pre-excited materials. This is not the case of incandescence; where upon heating a substance the spontaneous light emission is observed. There are three essential requirements for the production of thermoluminescence. Firstly, the material must be an insulator or a semiconductor. Metals do not exhibit any luminescence properties. Secondly, the material must have at some time absorbed energy during exposure to radiation for sake of excitation. Thirdly, the luminescence emission is triggered by heating the material. At this point it is noteworthy, that to observe the emission of light from the same specimen, it has to be re-excited and has to run for thermal scan freshly.

The fundamental principles which govern the production of TL are as same as those of all luminescence processes and in this way thermoluminescence is merely one of a large family of luminescence phenomena. Basically, during thermal run as Temp (T) rises carrier life time (τ) decreases and consequently the intensity increases as the electron become freed from the trap and recombination takes place, eventually as the trap becomes depleted; I(t) starts to decrease therefore, the resultant intensity versus temperature curve we get in the form of a peak.
To understand the mechanism and Phenomenological theory of this phenomenon, Clear grasp and understanding of following basic terms are highly essential.

[1] **EXCITATION**

It is the process by which the charge carriers lying in the valance band get excited and go to the conduction band e.g. irradiation.

[2] **TRAPS**

They are the localized energy levels near the conduction or valance band in forbidden gap which have high probability to capture holes or electrons in them.

[3] **DEFECTS**

Displacement of charge carriers atoms or molecules from their (regular site) original position is known as defects.

[4] **LUMINESCENCE CENTRES**

The localised discrete levels possessing high capture cross-section for excited electrons and having much greater possibility for radiation transitions are known as luminescence centres.

[5] **RADIATION**

The emission of energy from a source either in the form of wave or as a moving particles.
IRRADIATION:
When the ionizing or electromagnetic radiation source is exposed to the specimen of interest, then it is known as irradiation process.

STIMULATION:
The process of supplying external energy to release the trapped charge carriers from the traps e.g. heat. It reduces the lifetime of the trapped charge carriers.

ANNEALING AND QUenchING OR, THERMAL PRETREATMENT OR,
PRE-HEAT TREATMENT:
When the material is elevated at certain high temperature and held for quite long time and then suddenly brought to room temperature. This process is known as pre-heat treatment. One can have variety of processes, e.g. varying atmosphere of annealing, varying atmosphere of quenching, varying duration of pre-heat treatment, varying atmosphere of the furnace in which sample is to be kept usually, for this purpose i.e. annealing the sample, muffle furnace is used.

PHOSPHOR:
Any substance which exhibits the phenomena of luminescence is called as phosphors. Phosphors are generally crystalline material, they may be pure or impure, synthetic or natural, organic or inorganic substances. They may be of any form.
[10] **GLOW CURVE** :
The general way of displaying thermoluminescence data is by plotting a curve of luminescence intensity as a function of temperature. The area under each peak is related to number of filled traps.

[11] **TRAPPING PARAMETERS** :
The parameters which are associated with the trapped charge transfer process in the material are known as trapping parameters. It explains trap level spectroscopy partly or fully.

[12] **ACTIVATION ENERGY** :
The energy required to libreate the charge carrier from the trap is known as activation energy.

[13] **FREQUENCY FACTOR** :
The number of attempts to escape the trapped charge carrier per second. Its value depends on the type of traps.

[14] **LIFE TIME** :
The average time spent (storage time) of electron in a given type of trap is known as life time.

[15] **ORDER OF KINETICS** :
The expression which describes the rate process taking place during thermal stimulation for the two level model is known as order of kinetics.
[16] FIRST ORDER KINETICS:
If the probability of retrapping is negligible than the probability of recombination then such rate process is called first order kinetics.

[17] SECOND ORDER KINETICS:
If the probability of retrapping is not negligible then we say it as second order kinetics.

[18] RETRAPPING:
If thermally released charge carriers from the traps returned back in the traps then it is known as retrapping.

[19] RECOMBINATION:
If the thermally released charge carriers recombined with opposite charge carriers then it is known as recombination. If the supplied energy is more than the activation energy then only it is possible.

[F] MECHANISM OF TL EMISSION:
The phenomenon of TL in inorganic dielectric materials can be explained with the aid of band theory of solids. The large forbidden energy gap (~10 eV) between conduction & valance band is responsible to have many localised metastable energy levels due to defect levels present in the crystal lattice. It is these levels which are responsible for emission. This could be explained by the following simple model. The irradiation excites electrons from the valance to the conduction band most of the excited electrons return to the valance band after a very short period (~10 sec.) giving rise to
FIG.NO. II.1  Schematic representation of the mechanism of Thermoluminescence
luminescence which can be detected during the irradiation. Some of them however are trapped in local trapping levels within the forbidden gap (These traps are usually associated with lattice defects such as vacancies, interstitials, or impurities). Each trapped electron leaves a hole in the valance band which is soon trapped in a hole trap or recombines with a trapped electron. Since the valance band is full, a direct transition of a trapped electron to this band is improbable. However a trapped electron (or hole) can be thermally raised to the conduction (valance) band, move in the crystal, and finally recombine with a trapped charge carrier of the opposite sign. If those recombinations are radiative and take place during the heating of the sample, TL is observed. [fig.ii.1]

[6] THEORY OF THERMOLUMINESCENCE :

Electrons in the trap have a Maxwellian distribution of thermal energies therefore, the probability of escape of an electron from a trap of trap depth \( E \) (activation energy) is of the form:

\[
\begin{align*}
    p &= \frac{\exp \left( -\frac{E}{kT} \right)}{s}\ 
    \exp \left( -\frac{E}{kT} \right) \\
    &= s\cdot e^{-E/kT}.
\end{align*}
\]

Where \( k \) = Boltzmann's constant
\( T \) = Absolute Temperature
\( s \) = Frequency Factor (sec.)

Frequency factor \( s \) is constant but sometimes it is found to be dependent on the initial concentration of trapped electrons in a given type of trap. The simplest mathematical representation for the luminescence glow
peaks without any overlapping, is provided by the rate processes taking place during thermal stimulation for the simple two level model. By doing so the two assumptions normally employed are:

(i) That the free carrier concentration in the conduction band is always very much less than the trapped carrier concentration i.e. \( n \ll n_c \).

(ii) That the rate of change of the free carrier concentration is always very much less than the rate of change of the trapped carrier concentration.

\[
\text{i.e. } \frac{dn}{dt} \ll \frac{dn}{dt}_c
\]

This means that the free carrier concentration is approximately constant and does not require that \( n \ll n_c \).

This implies that the free carrier life time is much less than the trapped carrier life time. These assumptions have been widely used in the solution of differential equations, with and without the addition of thermally disconnected traps (8,9).

[a] RANDALL-WILKINS THEORY OF TL (10).

According to the Randall and Wilkins (10) the probability of retrapping is negligible compared to that of recombination; which is the case of first order kinetics. The luminescence intensity at any temperature is proportional to the rate of change of detrapping.
therefore, \( I(t) \propto -\frac{dn}{dt} \)
\[ I(t) = -c \cdot \frac{dn}{dt} \]

Where \( c \) is the proportionality factor which includes the radioactive transmission probability and the minus sign indicates the decrease of \( n \) with time.

\[ I(t) = -c \cdot n \cdot e^{-\frac{E}{kT}} \]

Where \( n \) = number of trapped electrons.

\[ \frac{dn}{n} = -c \cdot e^{-\frac{E}{kT}} \cdot \frac{dT}{dt} \]

Therefore, \( \frac{dn}{n} = -c \cdot e^{-\frac{E}{kT}} \cdot \frac{dT}{dt} \)

\[ \int_{0}^{T} -\frac{E}{kT} \]

Where \( p = \frac{dT}{dt} \) is the linear heating rate (K/sec.)

By integrating on both the sides, substituting in equation (2), we get

\[ I = n_0 \cdot c \cdot e^{-\frac{E}{kT} \cdot \int_{T_0}^{T} e^{-\frac{E}{kT}} \cdot dT} \]

Where \( n_0 \) = initial number of trapped electrons.

\[ -\frac{E}{kT} \]

At certain temperature \( T \), \( c \cdot e^{-\frac{E}{kT}} \) is a constant and is taken as \( A \), then using equation (2) we get,

\[ \frac{dn}{n} = -A \cdot dt \]

\[ n = n_0 \cdot e^{-A \cdot T} \]

We can write,

\[ I = I_0 \cdot e^{-A \cdot T} \]

Where,

\[ I = An \]

Thus at a fixed temperature \( T \), TL intensity decays
exponentially and the TL process is said to be following the first order kinetics.

[b] GARLICK GIBSON THEORY :

They considered the case where a free electron has equal probability for going to recombination centre and getting retrapped (11). If \( N \) is the total number of traps of which \( n \) are occupied at a time \( t \); the probability of the released electron going to the recombination centre is:

\[
\frac{n}{(N-n)+ n} = \frac{n}{N}
\]

Therefore;

\[
I = \frac{c.dn}{dt.n/N} = -\frac{E/kT}{2} = -c.s.e \cdot \frac{n}{N} \tag{5}
\]

By integrating equation (5) and rearranging equation for TL intensity is obtained as;

\[
I = \frac{n_0 c.s'e^{-E/kT}}{[1 + s'no/P \int_T^{T'} \exp(-E/kT') dT']^{2/3}} \tag{6}
\]

Where \( s' = s/N \) is called as preexponential constant, and has the unit cm\(^{-1}\) sec.

At a fixed temperature \( T \), equation for the TL intensity can be derived as

\[
I = I_0/[1 + A' n_0 t]^{2}
\]

Where \( A' = c.s' \exp. (-E/kT) \)

This process of luminescence follows second order kinetics;

[C] MAY-PARTRIDGE THEORY :
In many cases, the process follows neither the first order, nor the second order kinetics, Hay and Partridge gave the following equation which follows any non-first order kinetics,

\[ I = -c \frac{dn}{dt} \]

\[ = -cs' n \exp(-E/kT) \] \( \frac{1}{\left[(1-1)s'(no) \int_{\tau_0}^{\tau} \exp\left(-\frac{E}{kT} dT+1\right) \right]} \] \( 1/(1-1) \)

Where I is the order of kinetics and can have any value (not necessarily an integer).

Solving the equation we get the value of I as:

\[ I = s' n \frac{c \exp(-E/kT)}{\left[(1-1)s'(no) \int_{\tau_0}^{\tau} \exp\left(-\frac{E}{kT} dT+1\right) \right]} \] \( 1/(1-1) \)

\[ \int_{\tau_0}^{\tau} \exp\left(-\frac{E}{kT} dT+1\right) \] \( 1/(1-1) \)

s'no has unit sec and in this case it is similar to frequency factor s of first order case.

Thus,

\[ I = cs n \frac{\exp(-E/kT)}{\left[(1-1)s'(no) \int_{\tau_0}^{\tau} \exp\left(-\frac{E}{kT} dT+1\right) \right]} \] \( 1/(1-1) \)

\[ \int_{\tau_0}^{\tau} \exp\left(-\frac{E}{kT} dT+1\right) \] \( 1/(1-1) \)

This equation is not valid for \( l=1 \) but when \( l \to 1 \) it reduces to the first order case and when \( l \to 2 \) it reduces to the second order case. An examination of the kinetics when thermally disconnected traps are included has recently been developed by Chen et al. (13) and given as:

\[ I(t) = -\frac{dn}{dt} \]

\[ = s' n (n+m) \exp(-E/kT) \] \( \frac{1}{\left[(1-1)s'(no) \int_{\tau_0}^{\tau} \exp\left(-\frac{E}{kT} dT+1\right) \right]} \] \( 1/(1-1) \)
Where \( s' = \frac{s}{N + m} \) respectively,

Comparing this expression with first and second order kinetics equation, it is clear that this equation tends to the first order case when \( m \gg n \) and to the second order case when \( m \ll n \).

Where, \( m \) = concentration of thermally disconnected traps.

More meaningfully, the above equation can be expanded as:

\[
I(t) = s' m \cdot n \exp\left(-\frac{E}{kT}\right) + s' n \exp\left(-\frac{E}{kT}\right) + \ldots
\]

It looks like the addition of the first and second order expressions. For this reason it has been termed as "Mixed order Kinetics."

The solution of the equation is given as:

\[
I(t) = \frac{s' m}{\alpha^2} \left( \exp\left(\frac{ms'}{kT}\right) \int_0^T \exp\left(-\frac{E}{kT}\right) \,dT \right) \cdot \exp\left(-\frac{E}{kT}\right)
\]

Where, \( \alpha = \frac{n}{n+m} \)

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**Brief History of Thermoluminescence Research**

Probably the first scientifically recorded observation of TL was made in 1663 by Robert Boyle (14). Who observed a "Glimmering light" from a diamond upon warming it up. Boyle also stimulated the luminescence emission by more conventional means by using the heat from a hot iron; from friction and from a candle. In 1676 Elsholtz observed a similar effect from the mineral fluorspar. Early interpretations of the phenomena were that the heat itself
was being directly converted into light. Most of the other observations at the time supported this or similar views. Dufay thought that the luminescence was due to a sulphur which actually burned on heating but later he was to provide what was possibly the first clear evidence that the observed phenomenon (i.e. TL) was nothing more than the delayed phosphorescence (16). His experiments on natural quartz showed that the thermoluminescence could be reactivated by exposure of the light to the sample. Heat only stimulated the emission but was not its real cause. Some years later, the first account of thermoluminescence from extra terrestrial minerals was written by Alexander Herschel (17).

It is difficult to pin-point exactly when the word TL was first used, in the published literature, but it is certainly used in 1895 by Widemann and Schmidt (18) in what Becker (19) describes as probably the first careful investigation of experimentally radiation induced TL (Thermoluminescence) under its modern name. A major difference they made was that they induced TL themselves by irradiating the specimens with an electron beam in the Laboratory. This type of TL is sometimes referred to as 'artificial TL'. (where as, the earlier observations were on natural thermoluminescence) They studied a wide variety of synthetic phosphors. Trowbridge & Burback (20) published the fact that the thermoluminescence from natural specimens could be regenerated in the Laboratory.
The connection between phosphorescence and radiation was the subject of extensive examinations in the late nineteenth century (21) and the study of radiation induced thermoluminescence received a boost from Marie Curie (22). According to her the fluorite became luminous when heated; they are thermoluminescent. Their luminosity disappears after some time, but the capacity of becoming luminous a fresh through heat is restored to them by the action of spark and also by the action of radiation. At about this time the first thorough study of the spectra of the emitted TL was made by Morse (23). The mineral fluorspar was the subject of Morse's observations. Wick & his colleagues produced to make a thorough study of x-ray and electron beam induced thermoluminescence in selected natural as well as synthetic phosphors (24-25) included in these phosphors was CaSO doped with manganese. Magnese $^4$ became recognised as an especially good "activator" of luminescence and CaSO : $^4$Mn in particular was an excitement TL phosphor. This phosphor was used to detect UV radiation by Lyman (26). The degree of transparency of the air between the spark and the phosphor was deduced from the brightness of the thermoluminescence. In a sense Lyman's work was one of the earliest uses of thermoluminescence in dosimetry.

It was already been noted that the temperature at which the thermoluminescence peak maximum occurs is related to the electron trap depth. It was recognised by Urbach (27)
however it was not until the now famous paper by Randall and Wilkins, Garlick and Gibson (10-11), that any real progress was made in this regard. The occurrence of TSL during a thermal scan of previously excited material is probably the most direct evidence we have for the existence of electronic trap levels in these materials. Any TSL peak may be attributed to a species of traps. Its appearance is a direct representation of the fact that:

1) The escape probability of trapped carriers is a sharply increasing function of temperature and
2) The supply of trapped carriers is limited to start with and decreases with their ongoing thermal release from the traps. The location of a glow peak on the temperature scale provides encoded information on the value of the thermal activation energy (E). Hence a glow curve represents a spectrum of energies which are required to free carriers from the various pieces of traps in the material. The procedure used to decode the glow spectrum and extract the desired trap spectroscopic data appear obvious and straightforward.

**Factors affecting TL:**

The TL output depends on many factors as listed below:

(i) Effect of impurities:
An impurity in the phosphor is often called as "activator". Its presence plays an important role, particularly enhancement in trapping and emission centers which finally result high TL output.
(ii) Effect of thermal treatments:

TL properties exhibited by a phosphor very much depend upon the kind of thermal annealing experienced by it prior to the irradiation or excitation. Annealing is the process which reduces internal strain and surface energy. In some cases the TL sensitivity changes by the annealing treatment which can be identified with certain crystalline phase changes in the phosphor.

(iii) Effect of irradiation dose:

In many phosphors the thermoluminescence properties change considerably with the increase in the total irradiation dose. The significant effects of heavy irradiation are:

a) TL Sensitisation: TL sensitivity enhances with dose.

b) Damage of TL: On the other hand under the influence of higher dose of radiation, the crystal damage takes place under which the generation of voids, aggregates, strain location etc, can occur which reduces the TL output with or without a change in the TL emission spectrum.

(iv) Effect of LET of irradiation:

The ionisation capacity of a radiation in a medium is usually signified by the linear energy transferred (LET) to the medium by the incident energy. Usually the TL sensitivity decreases with the increase of LET of the incident radiation.
Effect of stress, crystallisation and particle sizes:
These Effects have been pursued in detail in the case of thermoluminescence exhibited by geological samples and they are almost inseparable in these cases.

Storage Effect:
This is essentially a 'fading' effect on the thermoluminescence (of a previously irradiated phosphor) at a constant temperature. The feeling characteristics of a phosphor can be best described by the life time \( T \) of the particular trapping state where in greater life time \( (T) \) value will mean less fading.

Thermal Quenching Effects:
The luminescence efficiency is generally a temperature sensitive factor, efficiency decreases with increases of temperature.

Electro Static Effects:
It has been observed that application of high electric fields on a TL phosphor during the heating enhances the TL output and sometimes affect the nature of the emission too.

Effect of Infra-red Stimulation:
The possibility of achieving the release of stored energy by IR stimulation rather than thermal stimulation has been observed very efficiently only in the case of alkaline earth sulphide (phosphors with shallow traps, where fading is quite high) with double activators.
APPLICATIONS OF THERMOLUMINESCENCE:

Thermoluminescence is perhaps one of those rare physical phenomenon which is more successfully applied than understood. Its application potential was first proposed in 1953. The prime motivators of this emergence of thermoluminescence as a practical research tool, in several different fields of applications were Farrington Daniels and his research group (29). The important aspects of such applications are briefly summarised in the following sections.

(a) Radiation dosimetry:

The intensity of thermoluminescence from a specimen is the result of a competition between trap filling by radiation and trap emptying by thermal excitation. At a given temperature of irradiation many materials display an intensity of thermoluminescence which is proportional to the amount of radiation absorbed, and this led Daniels and colleagues to propose that thermoluminescence may be used as a means of radiation dosimetry. Most research has been devoted to the discovery and development of materials suitable for thermoluminescence dosimeters. It had been known that the presence of impurities within a crystal enhances the thermoluminescence response and so it was that the sensitivity of LiF was found to be improved by incorporation of impurities. It was also realized that...
set by various pre and post irradiation annealing procedures. The Harshaw Chemical Company, Ohio, USA, developed the dosimeter TLD-100 which consists of LiF doped with approximately 170 mole p.p.m Mg and 10 mole p.p.m Ti. This material remain the most popular thermoluminescence dosimeter in use today.

(b) Age determination:

If the relationship between thermoluminescence intensity and absorbed radiation dose is established, it is easy to use TL as a means of age determination. This application of TL was also first suggested by Daniels and colleagues (29). The observation of natural thermoluminescence from samples of ancient pottery led to the immediate development of TL as a means of archaeological dating (30-31). The basic concept is that the ingredients of the pottery lose their accumulated geological dose when the pot is fired during its manufacture. Because of the high temperature experienced during firing the thermoluminescence level is reset to zero. The newly formed pot is now exposed to natural radiation from the radioactive elements naturally present in the clay and surroundings. Thus, the pottery now accumulates an absorbed dose which is proportional to its "archaeological age" i.e. the time since firing.

This age is calculated by equation:

\[
\text{age} = \frac{\text{absorbed dose}}{\text{dose rate}}
\]
Where, Absorbed dose = Archaeologically acquired TL

\[
\text{TL per unit dose of radiation} = \frac{\text{Annual dose from radioactive substance}}{\text{Dose rate}}
\]

With the improved methods of extracting the thermoluminescence grains from pottery the TL dating research progressed rapidly, as it gives the calculation of the natural dose rate.

(c) Geology:

The occurrence of natural thermoluminescence from rocks has long been known, e.g., Fluorite, Calcite etc. Daniels et al. stated that of over 3000 natural minerals studied, approximately 75% were found to exhibit natural thermoluminescence with measurable light intensity and remaining 25% were also thought to emit low level TL. They also proved the relationship between the natural radioactivity and the natural thermoluminescence. It was this relationship which led directly to the use of thermoluminescence as a means of arriving at the geological age of the specimen. However, age determination is not the only way that TL is used in geology. In some cases, TL is more sensitive for detecting traces of radioactivity than more conventional means. Thus, the technique has found widespread application in radioactive mineral prospecting. TL is also used for source identification. Many such specialized applications can be mentioned here. One aspect of geology in which TL is proving to be particularly useful is the study of meteorites and lunar material. More recently, the balance
between radiation filling of traps and the thermal emptying of them has been used to provide information related to the nearness of the meteorites to the sun whilst in space (i.e. their orbit) and to the time the meteorites have spent on earth (i.e. their terrestrial age) (32). A classification of rare meteorites also could be done using their TL properties.

(d) **Defects in Solids**

Our understanding of the nature of crystal defects has been increasing over the past 50 years or more due to the development of advanced experimental techniques. In principle, experiments on TL can be expected to yield useful information on the properties of the various types of defects present within an insulator or semiconductor. By now, it is well established that TL is particularly sensitive to traces of impurities within the specimen (34). In general, it is believed that the impurities give rise to the localized energy levels within the forbidden energy gap and that, these are crucial to the TL process. Townsend and Kelly concluded that the technique is capable of detecting as few as 10 defects levels, in a specimen (35), when coupled with the ability to separate the energies of these levels, TL provides, in principle at least a unique tool in the determination of the distribution of the defect energies. However it is meaningless to use TL alone to describe the defect structure of a solid, it is a very useful technique when combined with other measurements.
Apart from mentioned applications several novel applications have been discovered recently. In Biology, TL from DNA base analogues has been observed (36). These materials act as tumor inhibitors by a mechanism of radial conversion and it is hoped that TL will help us to understand the charge transfer processes involved. A complete list of applications of TL would also include the use of suitable phosphors for image storage devices, a test for fire damage in building materials, a quality control tool for ceramics and an aid in Forensic Science. Thus, TL has proved itself to be a technique of immense versatility.
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