CHAPTER - 2

FLAMMABILITY OF TEXTILES

2.1 MECHANISM OF BURNING

The decomposition of materials due to fire is called Pyrolysis. All textile fibres in their natural form are inherently fire retardants. Almost all known fibres have high flash point or melting point (Table 2.1). However, when the surrounding temperature reaches above the flash point temperature of fibres, they catch fire. Cellulose like cotton is solid and has appreciably low vapour pressure. They do not burn, but decomposes into flammable fragments, which generate heat. This heat further decomposes the cellulose to carry on the decomposition process. Thermal decomposition of cellulose leads to the formation of products like liquids, tar and solid materials. Bond rupture, bond reformation, volatilization and many exothermic reactions occur simultaneously. Catching of fire and its progress in textiles is mainly due to the formation of various gases and liquids during burning of fibre.[5]

Burning of material is a complex phenomenon. It involves processes such as heat transfer, thermal decomposition, etc. For synthetic fibres, the thermoplastic behaviour adds to the effect. Material like textiles made of cellulose fibres when burn, combustible vapour is generated and char is formed. When the flash point is reached, run away exothermic reactions are triggered. This is accompanied by appearance of flame or glowing zone. This phenomenon is known as ignition. The time interval between the onset of heating and ignition is called ignition time. The behaviour of thermoplastic material towards the flame/heating has a different story. Fabric made of synthetic material exhibit melting and surface involved in afterglow is different than in flaming. Prevention method of afterglow is also different. Afterglow is mainly due to the burning of remnant char, which forms due to lack of oxygen in surrounding atmosphere. Carbon and oxygen react to form carbon monoxide (CO). It is an exothermic reaction and energy liberated is 26.4 kcal. The char becomes ash in afterglow process by conversion of CO to CO_2 in presence of excess oxygen. This reaction is also an exothermic reaction and the energy involved

Table 2.1 Flash Points and Burning Behaviour of Various Textile Fibres

Name of Fibre	Temperature (°C)			LOI (%)	Flame Characteristics
	Ignition	Decompo-sition	Maximum Flame		
Cotton	400	305-320	866	18.4	Burns readily with ash char formation and after glow
Rayon	420	-	850	18.7	Burns readily with ash char formation and after glow
Acetate	475	300	960	-	Burns and melts ahead of flame
Triacetate	540	-	885	18.4	Burns readily and melts
Nylon 6	530	365-315	875	20.1	Melts and forms hard bead. Supports combustion with difficulty
Nylon 66	532	345	-	20.1	Melts and forms hard bead. Does not readily supports combustion
Polyester	450	400	697	20.6	Burns readily with sooth
Acrylic	560	287	885	18.2	Burning readily with melting and sputtering
Polyethylene	570	400	-		Burns slowly
Polypropylene	570	400	839	18.6	Burns slowly
Wool	600	300	941	25.2	Burns readily and form hair burning smell
Nomex	-	420	-	-	Combustion with difficulty
PTFE	>327	400	-	95	Do not easily burn

is 94.3 kcal, almost four times than that involved in CO formation. As ignition, shrinkage, melting, dripping and afterglow are involved, high energy and large amount of heat is evolved during burning.[5]

Polymer burning in general takes place in a series of stages. The first stage however, is almost inevitable and often termed as thermal decomposition. The thermal decomposition of the polymer yields volatiles or gaseous products; they continue to burn by the chain propagation process associated with free radicals. The basic understanding of the mechanism by which the polymers decompose is necessary; the in-depth study of every polymer burning is essential.

All common apparel textiles will ignite in air, if exposed to a flame or other heat source of adequate intensity for a sufficient period. Once ignited, large difference in their burning behaviour becomes apparent and hence the intensity of injury caused to the human skin varies with different textile materials. However, it is important to understand the flammability behaviour of individual fibres in order to predict the flammability behaviour of combination of fibres in fabric form and this effect on burn severity.

The action of heat on a textile material gives rise to a complex and inter-related series of physical and chemical effects. Clearly, the burning process of even simple fabrics is not that simple and several reviews exist in which fabric flammability is related to fabric properties such as fibre type, fibre blend ratio, mass per unit area and fabric construction.[6-11]

Lewin[12] explains flammability as the tendency of a material to burn with a flame. Indeed the flammability of textiles is a measurement of the ease with which fabric can be ignited and how effectively it burns.

Kasem and Rouette[13] profess that ignitability of the fabric as well as combustibility are the indicators of fabric flammability characteristics. The combustibility of the fabric is stated at the rate at which the flame (or the afterglow) is able to propagate. Backer *et al.*[14] described ignition of the fabric is as a more complex phenomenon. Ignition involves the transfer of heat with thermal decomposition governed by fluid mechanics and chemical kinetics. Exothermic reactions are triggered as the ignition temperature of the fabric is reached. The reactions accompanied by a flame or glowing of any sort is termed as ignition.

The burning process of textiles as stated by Reeves, Drake and Perkins[15] involves the release of heat, decomposition of the material, combustion and propagation of the flame. The decomposition of the material is explained as the breakdown of the hydrogen bonds that make up the composition of the fabric. Pailthorpe[16] explains that the fabric is broken down into gaseous liquid and solid composites, which further fuel the combustion process. His theory is in agreement with Lewin[12] who provides a diagrammatical representation of the burning process.

Perkins *et al.*[15] discussed the combustion process in detail, which includes the notion of flaming, glowing and smoldering. Glowing is explained as the release of radiant heat and the existence of a luminescence without the flame termed 'smoldering', occurs beneath the surface of the fabric at low oxygen levels. The reaction is exothermic and occurs in conditions of high oxygen levels. The slow suppressed exothermic reaction, termed 'smoldering', occurs beneath the surface of the fabric at low oxygen levels.

2.2 FACTORS INFLUENCING FLAMMABILITY CHARACTERISTICS

Bhatnagar[17] in his report titled `Flammability of Apparel' based on the research of Reeves[18] classified following three principal groups of fabric properties that dictate their flammability characteristics:

- Physical properties
- Chemical properties
- Thermal properties

The physical properties of the fabric include its mass, construction and configuration. Kasem and Rouette[13] also pointed out that the mass per unit area is directly proportional to the ease of ignition and linear burning rate. Denser and heavier the fabric, longer it takes to ignite and longer it takes to burn. The construction of the fabric is referred to as the smoothness of the surface of the fabric. Saddler *et al.*[19] discussed the notion regarding the configuration of the fabric. They explained that a tightly configure fabric reduces the level of oxygen available to support combustion. A knitted textile is more porous hence ignite and burn faster than a woven fabric.

Bhatnagar[17] point out that fire is a chemical reaction; therefore the chemical properties of any fabric influence its flammability characteristics. The fibres used in the fabrication, determine chemical properties of the fabric. Pailthorpe[16] noted in his report regarding the Flammability of Textiles that the textiles with higher concentrations of carbon were less reactive to fire in comparison to those with a low concentration.

Reeves and Drake[20] defined thermal properties of fabric as the ability of textiles to absorb heat, which can ordain its ignition temperature and burning rate. They noted that the condition under which the fabric is tested affect its flammability characteristics. The level of moisture presents in the atmosphere and hence the ability of the fabric to absorb the moisture will deter its burning ability.

The major variables which influence the burning of fabrics are: i) fibre type and content, ii) fabric mass, iii) fabric structure, iv) geometry of garment and configuration.[21-24] The weave pattern, yarn twist and possibly the linear density of yarns also to some extent alter the burning rates of cellulosic and thermoplastic materials. The dynamic process of fabric burning is also influenced by the surrounding conditions such as temperature, relative humidity, oxygen content, rate of airflow and orientation of fabric, for example ignition at the base of the vertically oriented fabric provides the highest burning rate for a given sample.[25] The effect of garment fit and garment configuration complicates the burning behaviour.

2.3 IGNITION

Ignition of fabrics (apparel, upholstery, bedding materials etc.) subjected to open flames is a topic of much relevance in understanding and controlling the initiation of unwanted fires. The ignitability of materials is of basic importance when fire initiation and developments are analysed. For example, in order to predict the burning behaviour of fabrics, it is crucial to understand the role played by various physical and chemical properties in determining:

i) Whether ignition would occur and

ii) If it does occur, the duration of exposure to accomplish it.

As pointed out by Saurer[26], knowledge of whether ignition or charring takes place may also be important in determining the nature of burn injuries.

2.3.1 Ignition Types and Definitions

Ignition follows from the chemical degradation of solid upon continued heating, which is into char and flammable volatiles.[27] If the volatiles mix with oxygen and are sufficiently hot then ignition will occur to yield flame. Atrey *et al.*[28] defined ignition as the appearance of a flame in the volatile gas stream evolved from a solid due to external heating (usually by radiation). The type of ignition may be either spontaneous or piloted. For piloted ignition, the mixture of fuel vapours and air in the proximity of an exposed flame remains within the flammability limits of composition, but it needs an external source of heat (such as a pilot flame) to initiate ignition. Whereas, for spontaneous ignition, the mixture in addition to being within the flammability limits is also in such a thermal condition that it can automatically react in an accelerating exothermic manner to yield a flame without the aid of any external, local energy source.[29]

Bamford *et al.*[30] in 1946 carried out the earliest known scientific investigation into piloted ignition of wood. They studied the ignition threshold by noting the time at which flaming would persist upon removal of the pilot heat source and postulated a critical lower limit pyrolysate mass flow rate criterion for sustained ignition. This criterion stipulates that, if the pyrolysate mass flux at the fuel surface is less than 2.5×10^{-4} g/cm^2/s, sustained ignition is possible.

In 1959, Akita[29] published a summary of comprehensive experimental and theoretical works on spontaneous and piloted ignition of cellulosic solids and presented evidence to show that ignition occurs due to some thermal phenomenon directly pertaining to the exposed surface itself. Formation of a combustible gas mixture in the proximity of the exposed surface in itself is a necessary and sufficient condition for piloted ignition (since an external heat source already exists). Such a condition is necessary but not sufficient to ensure spontaneous ignition. This sufficiency is fulfilled by a thermal condition at the attainment of a temperature above 500°C by the exposed surface.

In 1964, Martin[31] published his work on ignition and demonstrated that,

i) Although the internal temperature profile is considerably influenced by pyrolysis, a critical exposed surface temperature criterion describes the onset of ignition.

ii) The persistence of ignition depends only upon the continued outflow of flammable pyrolysis products but not on any unique composition of such pyrolysis product mixture.

iii) The exposed surface is completely pyrolysed long before ignition.

Further, Miller *et al.*[32] defined critical ignition time (CIT) as the shortest exposure time producing ignition for at least 50% of the cumulative results. They analysed the ignition time data for fabrics based on individual 'yes'-'no' results obtained from series of pre-defined exposure times. Table 2.2 shows the results of 'yes'-'no' trials for fabrics (cotton, polyester: cotton, rayon and wool) exposed to igniting flames for pre-selected times. They assumed that if a specimen ignites to a flame for a given time, it would also have ignited if the exposure had been longer. Conversely, if it does not ignite in a given time, it would not have ignited in a shorter time. Table 2.2 also shows the cumulative data for a particular fabric specimen. The average critical ignition time is 1.88 s.

Transient flaming ignition as defined by Broido and Martin[33], is the ignition in which the flames terminate promptly upon termination of the radiant (or convective) heating, whereas, sustained flaming ignition is that in which the flaming extends beyond the termination of the exposure and results in the nearly complete consumption of the solid.

Thomson and Drydale[34] defined critical ignition temperature as the surface temperature of material at which ignition occurs. Furthermore, the piloted ignition temperature can be defined as the lowest temperature at which the ignition of the decomposition products gives rise to sustained burning at the surface. It is similar to the fire point of a combustible liquid, but differs in what it refers to a surface temperature rather than a bulk temperature.

Table 2.2 Ignition Time Data

Time(s)	1.50	1.63	1.75	1.88	2.00	2.13	2.25
Yes	0	1	2	2	3	3	4
No	4	3	2	2	1	1	0
ΣYes	0	1	3	5	8	11	15
ΣNo	13	9	6	4	2	1	0

In 1979, Pintauto and Buchanam[35] also concluded that the basic mechanism of the ignitions is auto ignition and piloted ignition. Auto ignition depends on relative heat transfer process, when the material is subjected to an environment of hot gases (air) or to a radiant energy source. In such cases no spark or flame is necessary to ignite ignition, but piloted ignition occurs as a result of direct flame impingement process.

Thus, any definition of ignitability of a combustible material must incorporate the response of its surface to an imposed heat flux.

2.3.2 Ignition of Textiles

Number of researchers had studied the ignition of various textiles and garments.[36-38] Wulff *et al.*[39] for the first time postulated that the fabric ignition probability is a function of the quotient of exposure time divided by ignition time, and that the exposure time is dictated by human response and activities, while the ignition time is the characteristic of fabric properties and exposure.

Textile materials have very high fibre surface to mass ratios and hence tend to ignite easily and burn faster than other materials. Different fabrics exhibit different rate of ignition and ease of ignition depending on fabric mass. The heavier the fabric, the longer it takes to ignite than a light sheer fabric made of same material. Surface characteristics off course have a bearing on this factor. A loose pile fabric usually ignites more easily than compact smooth surface fabric.[40] The raised fibres have a much larger exposed surface and can ignite easily with a rapid flash of fire across the fabric surface. In some cases, these surface flashes may cause the entire fabric to burn, but in others, the surface flash may not produce enough heat to ignite the base fabric. Thermoplastic fibres such as polyamide and polyester are difficult to ignite and generally require a highly combustible source such as cotton to sustain ignition as they often self extinguish, because melted polymer falls away, carrying away heat and flaming material from the ignition source and zone. Lighter fabrics made from thermoplastic fibres exhibit 'Self extinguishing' properties whereas the heavier fabrics continue to burn readily due to the greater cohesion of the melting polymer.

Ignition of fabrics is much more rapid at a cut edge than at the surface. Both edge and surface ignition of cotton and blended polyester:cotton fabrics increases as the mass of the fabric increases. Surface ignition time per unit mass of fabric is more than edge ignition. Surface ignition time in case of cotton as well as polyester:cotton fabric is twice than that of edge ignition and the difference is much greater for heavier fabrics.[41]

The burning of polyester:cotton blended textiles are far more intense and hazardous than expected from the average flammability of the individual blend component. Cotton begins to decompose thermally at about 350°C whereas polyester decomposes at 420°-447°C. Flammable pyrolysis vapours are more readily formed from the cotton component, which ignites in the presence of sufficient oxygen. However due to the thermoplastic behaviour of polyester it shrinks and then melts (above 260°C) before the pyrolysis of cotton occurs. This melting of polyester envelops the surface of the polyester and cotton fibres developing carbonaceous char, which prevents any shrinkage of the blended fabric keeping it away from an approaching flame or igniting source. Moreover, the cellulosic carbonaceous char not only supports the molten polyester but also act as a wick into the flame source, thus enhancing the fuel supply within the flame zone.[42] This so called 'scaffolding effect' causes extremely intensive burning of polyester:cotton blended fabrics which combine the high flame temperature of cotton and the ability to adhere to the victim due to the presence of molten polymer. Several workers have suggested that such burning blend combinations are even synergistic in their behaviour and that the rate of heat release from polyester:cotton blends is proportional to the cotton content but the rate of burning is controlled by polyester content.[9,43] In case of regenerated fibres such as acetate and triacetate, woven fabrics often ignite and burn vigorously, while knitted fabrics tend to shrink from the flames and do not ignite and burn as readily.

Protein fibres such as silk and wool are more difficult to ignite. It takes twice as much heat to ignite wool as cotton and wool extinguishes more quickly in moving air.[44] Because of their nitrogen contents and in the case of wool, its sulphur content, both silk and wool fibres have low intrinsic flammability with limiting Oxygen Index (LOI) values of 23% and 25% respectively. Wool is in the class of fibres, which char and burn but it does so to a lesser degree and at a slower rate than the other fibres in this class, namely acrylics and cellulosics.

2.4 FLAME TEMPERATURES AND HEAT RELEASE

Flame temperature is a sensitive indicator of interactions that occur once material begins to burn. Miller and Martin[32] have extensively reviewed fabric flame temperatures of blended fabrics. They observed that flame temperature of some multi-component fibrous system is the same as that of the hotter burning component. For example 100% cotton fabric burns at 1000°C and 100% polyester burns at 850°C, but the polyester:cotton 50:50 blend fabric burns at about 950°C. It is considered that no additional chemical reactions are occurring. Whereas, there are some blends, which burn at an average flame temperature of the two components, suggesting chemical interaction between the components.

Table 2.3 shows flame temperature of various double fabrics layers. It can be seen that fabrics with cotton blends burn with much higher temperature than that of thermoplastic component of the blend. Carter and Finley[43] further studied the effect of blend ratio on flame temperatures of polyester:cotton fabrics and found that fabrics with higher polyester content burn with lower flame temperature.

Table 2.3 Flame Temperatures of Double Layer Fabrics (Horizontal Burning)[45]

Type of Fabric	Flame Temperature at 21% O_2 (°C)
Non interacting fabrics:	
Cotton-acrylic	976
Cotton-Cotton	974
Cotton-polyester	950
Polyester-polyester	649
Acrylic-acrylic	910
Nylon-nylon	860
Interacting fabrics:	
Acrylic-nylon	942
Cotton-nylon	902

Once the fabric is ignited, the flame size increases and the heat emission reach its peak value, which is followed by heat transfer and hence rapid cooling thereafter. Miller and Meiser[46] have defined the two terms; heat emission and heat transfer distinctively. Heat emission refers to energy given off by a material during flaming combustion, although the destination of this energy is not specified. Heat transfer on the other hand, implies and by necessity requires the identification of a specific target.

Wright *et al.*[47] studied the heat transfer from burning fabrics and noted that the peak heat release occurs as soon as the lightweight fabric is ignited. They developed a calorimeter to measure the heat release rate from burning fabrics and studied the effect of fabric area density or weight on heat transfer rate. For cotton the heat emission is inversely proportional to the fabric weight whereas for 100% polyester, it is directly proportional to the fabric weight but to a much lesser extent.

Miller *et al.*[9, 45, 48] used the TRI convection calorimeter to measure the heat release rate of blended fabrics and found that heat emission is strongly influenced by the fibre type. Fabrics of the same weight but manufactured with different fibres have been shown to produce different heat outputs. For example, viscose rayon and cotton emit less heat per unit volume as compared to that by regenerated acetate. In general, the more the carbon and hydrogen present in the chemical structure, the more the heat emission when material burns. Thus, many synthetics have a potential to give off more heat when they burn than that an equivalent amount of a cellulosic material, off course the rate of heat release will vary. Moreover, the melting residue of polyester and nylon fibres holds heat and cools very slowly to form a bead like plastic residue. These melting residues are at very high temperatures and can cause severe skin injury as they shrink and tend to stick to the skin.

The heat produced when blended fabrics burn is often not a simple additive function of the heat produced by the pure component fibres. Thus, in case of polyester:cotton blends, the molten component (e.g. polyester) is prevented from dripping and is held by the non thermoplastic component (e.g. cotton). Furthermore, polyester, which normally burns at a low temperature of 480°C, is forced to burn at the higher cotton flame temperature of 1000°C, thus increasing the rate of heat output as discussed above. Increasing oxygen supply usually promotes burning but does not necessarily increase the heat emission. However, the flame temperature does increase with increase in the oxygen content.

2.5 FLAME SPREAD

Flame spread is influenced by various clothing structural factors such as presence of belts, ties, cuffs and collars and tight fitting areas, since they act as fire stops. Loose fitting or flowing garments exhibit the so-called chimney effect, which makes the flame spread more rapidly up vertical to fabrics. Moreover, full-length nightdresses burn more vigorously than knee length garments of the same fabric. The flame spread is particularly rapid in the lightweight fabrics selected for nightwear if the more flammable fibres are present.

Besides fabric structural effects, Miller and Goswami[49] have analysed the effect of various yarn parameters on the burning behaviour of the fabrics.

They found that no twist yarns show higher burning rate values. The yarns with twist from 0 to 1.37 turns per cm decrease the mass burning rate by up to 40%. Thus the low flammability of the twisted yarns can be attributed to the reduction of voids in the yarn. This has two effects, the first is the reduced access of fibre surfaces to air and hence reduced combustion rates; and the second is the greater thermal conductivity across fibres in the yarn cross section which could be expected to increase burning rates. The first effect appears to be the predominant one.

Moussa *et al.*[50] observed different flame spreading mechanisms for different textile materials and their findings are summarized here:

- For cellulosic fabrics, the important physical process is the heat transfer from the flame to the virgin material and the generation and diffusion of the combustible vapours to the fuel flame.
- The fine structure of the cellulose has no apparent effect on the flame spreading mechanisms.
- Materials of different porosities and of different interlacing geometries are found to have same flame spreading speed.
- In case of thermoplastic fabrics, shrinking, melting and dripping play important roles in the flame spreading mechanism. High shrinking levels may even extinguish the flame. Dripping can cause a reduction or increase in flame size, a fire jump and/or a change in the flow field around the fabric.
- For blended fabrics, both the process characteristics of cellulose and thermoplastics are observed.
- For fuzzy cellulosic materials, a flashing flame consumes the outer layer of fuzz whereas the interior layer may smoulder instead of burning.

Markstein *et al.*[51] studied the upward fire spread over textiles in details. He attempted to solve the complexity of the problem by number of simplifying assumptions such as:

i) Two dimensionality of flow, ii) neglect of gas phase chemical kinetic phenomena, iii) neglect of details of pyrolysis iv) neglect of edge spread phenomena, and (v) neglect of detailed effects of fabrics construction.

Their experiments and theoretical study lead to following conclusions:

- Two dimensionally upward flame spread over cotton fabrics remain laminar for only a short initial period, after which the flames rapidly assume a highly turbulent character.
- The flame tip positions above and below the fabric remained essentially coincident, regardless of angle of inclination of the fabric. The upper individual flames detach partially, the effective heat transfer length of the upper flames is thus appreciably smaller than the lower ones.
- The acceleration is characterized by a power law relationship between pyrolysis spread rate and pyrolysing length l_p, $V_p = \beta l_p^n$ with $n<1$, this relationship implies asymptotic attainment of a constant spread rate $V_{p\infty}$ which however, cannot normally be realized with practical dimensions of the test fabric.

2.6 MEASUREMENT OF FABRIC FLAMMABILITY

The flammability of a fabric is measured in most of the standard tests in terms of ignitability, combustibility and extinguishability. Additional measurable characteristics, which are more scientifically based, can be categorized under the headings:

- Pre-ignition: i) thermal decomposition (temperature and weight losses) ii) enthalpy changes iii) products of thermal decomposition and iv) kinetics of the ignition process.
- Post-ignition: i) ignition temperature ii) flame temperature iii) heat release rates during burning iv) flame propagation rates v) upward mass burning rates vi) extinguishability and vii) products of combustion.

Many research investigations have been initially aimed at the further classification of the burning hazard of self-extinguishing and flammable fabrics. Self-extinguishing fabrics are those, which stop burning after removal of an ignition source. Such fabrics are often required for clothing for persons, who cannot be expected to respond effectively when they find their clothing catching on fire, such as children and hospital patients, and for clothing of workers routinely exposed to heat and fire. The usual criteria for self-extinguishing fabrics are char length, after flame and afterglow time, and presence of melt drip.

It is generally understood that flammable fabrics are those fabrics, which ignite when subjected to a small flame for durations of up to 12 seconds.[52] Most of the work on flammable fabrics is therefore concerned and directed towards the observation and measurement of ease of ignition, the rate and extent of flame spread, the duration of flaming and measurement of heat release and heat of combustion.

2.6.1 Fabric Ignition Measurement Techniques

During the 1970s, the experimental techniques such as Oxygen Index (OI) and flame temperature methods gained popularity for measurement of flammability. According to the ASTM: D286373, Limiting Oxygen Index (LOI) is defined as the minimum concentration of oxygen, expressed as volume percent, in a mixture of oxygen and nitrogen that will just support flaming combustion of a material. However, this technique provides a numerical data regarding flammability, but it does not explain the burning behaviour of the material. With respect to textiles, OI tests are mainly used in determining the effects of different flame retardant treatments and finishes, varying the add on of finishes, or varying synergetic combinations of flame retardant compounds. In the case of ignition, auto-ignition temperatures, softening and shrinkage temperatures of various fibres are listed in the literature however the methods for obtaining the various values are not specified.[53-56] Gottlieb and Beck[53] determined ignition temperatures for most common commercial fibres. The procedures used consisted of forming 250 mg balls of the fibres and placing them into a furnace at a given temperature. Ignition and no ignition conditions were noted. The same investigators determined the temperature at which

50% of the fibre balls had decomposed. They also obtained the same values for fibre balls containing of 50:50 blends of the various fibres and cotton.

Sayers[57] performed series of simple experiments to determine the ignition temperature of different fibres by dropping the fabric samples, which were pre-conditioned at the ambient temperature onto a hot plate heated to range of temperatures. The ignition temperature was defined as the hot plate temperature at which the sample ignited. Fibre ignition temperatures thus obtained are listed in Table 2.4. It was also stated that fibres with similar ignition temperatures could exhibit very different burning characteristics.

Setchkin[58] developed more scientific method of determining fabric ignition or melting temperature. The modified Setchkin Furnace was used as a part of the ASTM D1929-68 Standard Test for Ignition Properties of Plastics. Wulff *et al.*[59] further developed more sophisticated apparatus called "Radioactive Ignition Time Apparatus" for determining fabric ignition time. Ignition time was recorded from the sudden rise in the oscillogram of the signal from the IR detector. Ignition time or melting time was recorded as a function of heating power flux.

Table 2.4 Fibre Ignition Temperatures of Various Fibres

Fibre Type	Ignition Temperature (°C)
Cotton	400
Acetate	525
Nylon 6	530
Triacetate	540
Acrylics	560
Polypropylene	570
Wool	600
Fibrolane	625
Teklan	690

2.6.2 Flame Spread Measurement Techniques

Various flame spread theories were developed in 1970s, which formed the basis of standard test methods designed for measuring fabric flame spread. [51,60-64] The theoretical models to predict flame spread behaviour were developed on the basis of measured burn length using video photography. Some of the methods of measuring fabric flame spread involving different techniques to those above and related theories are briefly discussed below:

One of the ways of measuring vertical flame spread is to weigh the burning sample continuously. This would enable to calculate the rate of loss of weight to be calculated of the sample. To calculate vertical flame spread Lawson *et al.*[64] discussed the details of the apparatus designed for measuring the vertical flame spread on fabrics by above principle.

An alternative method of assessing flammability was developed, to allow the material to burn at various angles to the vertical and to see at which angle the sample is no longer able to support flaming. Lawson *et al.*[61] designed a simple apparatus; wherein a sample spread over a semicircular track was ignited at one end and the distance to which the flame spread reached was noted. It was found that many materials burned completely round the semicircular track, and they were differentiated from each other by noting the time taken to burn 53.3 cm (21 inches) long specimen.

They also derived two empirical mathematical equations for determining flame spread rate (V) and concluded that the vertical flame speed is roughly proportional to the square root of the distance of flame (d); ($V=1.81\ d^{0.4}$) and inversely proportional to the time of spread of flame (T); ($V=1655/T^{1.03}$) for the materials that burn completely (for flammable materials).

Following this work, Webster[62] continued to test the feasibility and validity of the empirical equations derived for the vertical flame spread (V) in terms of flame spread distance (d) and time of spread of flame (T). He tried to combine two empirical equations into one for calculating flame spread ($VT=0.31d^{2.5}$).

This was of more significance to the fabrics, which did not spread flame around the complete semicircle.

Thomas and Webster[63] investigated the effect of varying width on the rate of flame spread and also measured the height of buoyant diffusion flames. They found that the fuel velocity at the base of the flame is very small compared to the velocities higher up the flames, which are determined by the buoyancy. Further, velocity controls the rate of entrainment of air into the flame zone, which is largely independent of the rate of entry of fuel into the flame.

It is therefore, desirable either to modify existing test methods or to develop a new small scale test method so as to assess the flammability characteristics of the saree fabrics for better understanding of the correlations of fabric behaviour and the resultant burn injury severity.

2.7 HEAT RELEASE MEASUREMENT TECHNIQUES

Heat release measurement is also a significant criterion in assessing fabric flammability. Fabric heat release tests have been designed to generate data such as maximum, average or total heat released to the heat sensors. Heat transfer from burning fabrics has been measured by various apparatus types ranging from simple cylinders to very sophisticated instrumented mannequins. However, there are only two cases where heat evolution from textiles fabrics has been considered for regulatory purposes. One is the Australian Standard AS 117634, in which heat developed by burning specimen is measured by means of copper rod located near the cabinet designed for the flame-spread test. The other is the general apparel flammability standard developed by the National Bureau of Standards for the US Consumer Product Safety Committee (CPSC). The test instrument used for this standard is called the Mushroom Apparel Flammability Tester (MAFT).[64] The specimen is a cylinder, 178 mm in diameter and 300 mm high, simulating a pant leg or a skirt. It surrounds a copper cylinder and closed on top by a plate. There are in all 20 thermocouples, which are used to measure the heat release rate from the burning fabric. The MAFT method was originally designed for pass-fail use, but it has been used to measure heat evolution from many FR and treated fabrics.

The tests designed to measure heat release rates and thus predict burn injury severity differed mainly in the manner in which the specimens were held, the number of sensors and the manner in which they were mounted relative to the specimen and the specimen shape.

Birky and Yeh[65] measured both heat of burning (H_b) and rate of heat generation of several textiles. Some of their results are shown in Table 2.5. The major use of heat evolution measurements for determining fabric burn hazard has been in mannequin burns or similar simulations of fire accidents. Sensor systems used on mannequins rank from paper that turn black at certain temperatures to sophisticated sensor systems, which indicate the depth of burn.[66-68]

Mannequin tests and thermally instrumented female torsos were developed to determine the burning behaviour of full size garments and to study the resultant burn injury severity. The use of such mannequin tests and thermally

Table 2.5 Heat Generation Capacity of Different Textiles

Fabric Type	H_b Cal/g	H_r Cal/s cm	H_c Cal/g	H_L (%)
Cotton	3315	78.3	3688	89.9
Acrylic	4118	43.7	7020	58.7
Polyester[e]	2188	17.5	5255	41.6
Nylon[e]	3715	13.2	6929	53.6
Poly:cotton (65:35)	2776	69.5	4907	56.6

H_b- Heat of burning in air, H_r- Rate of heat generation per unit sample width H_c-Heat of combustion in oxygen bomb calorimeter, H_L- Percent of H_c liberated by burning in air.

[e] Cotton gauze underlay required as ignition source.

instrumented female torsos has been thoroughly reviewed by Kransy[67] and Mortiz *et al.*[68] respectively. These tests offer more analytical means of assessing apparel burning hazards and predict potential skin burn hazards of garments. They are useful in research but are very expensive and complex to be used in standard test procedures.[69]

Very recently, heat release rate data has been used as a tool for evaluating the hazard level of a fire system.[70] The cone calorimeter measures the hazard level by measuring the rate and amount of heat released, smoke and toxic gases generated. The rate of heat release is determined by measuring combustion product gas flow and oxygen depletion, while the mass loss is also recorded simultaneously. Like other calorimeters,
the major role of cone calorimetry, whereas other calorimeters measure heat released by measuring rise in temperature (e.g. isoperbiol calorimeter) or by measuring the air entrained during burning of specimen (e.g. TRI convection calorimeter discussed above). The cone calorimeter measures the following parameters during a test:

i) Sample mass
ii) Time of ignition
iii) Flow rate and temperature of the exhaust gases
iv) Oxygen and Carbon Oxides (CO and CO_2) in the exhaust gases; and
v) Smoke density

2.8 FLAMMABILITY REGULATIONS AND STANDARDS

Textile fabric and garment design features as well as factors unique to each wearer individually and collectively are influenced by the age, gender, health, social and ethnic background and educational level. Thus the flammability hazard of any fabric/garment cannot be judged only on the basis of flammability characteristics of a particular fabric.

Assessment of the potential flammability hazard of any fabric can be attempted if the source of danger and injury to the body is identified at each stage of burning process.[71] An example of a worst possible situation is, when loosely hanging clothing is exposed to source of ignition such as an open fire, cooker flames and smokers materials, once ignited, flames may spread quickly and the wearer may receive burns up to 70% area of body surface in a matter of seconds. This type of burn would permanently disfigure the person lucky enough to survive.

During past twenty years the governments of US, Canada, UK, Australia and many other European countries have enacted legislation aimed at reducing the hazard of fabric burning. The issue of hazard posed by loose fitting nightwear and its association with severe burn injuries continues to receive attention and consequently, the European Union is currently assessing the hazards posed by nightwear and considering whether regulations are required to reduce it.[72]

Of the current textile flammability regulations, which have the significant impact on industry and the consumer, are those concerning the children's sleepwear. The criteria for children's sleepwear are more stringent than those for general apparel as the statistics indicate that this former group of the population is highly vulnerable.[73,74] This issue has been recognized and the regulations are imposed for the safety of people in UK, USA, Canada and Australia.[75]

In India no such regulation exists, as the causalities and hazards posed by fires are not yet studied comprehensively. A specific group can be located and precautionary measures be adopted to avoid these fire incidences. Interest has therefore grown in analysing fire statistics in India and studies in detail regarding contribution of each factor catalyzing fire and warning people about such safety precautions. Furthermore, as the demands by consumers for safety increase, these issues are matters of concern not only to the textile industry, but also to consumer bodies, legislators and medical profession. [76]

2.9 NEED OF SAFETY REGULATIONS

The basic requirement of any flammable fabric regulation is that it should be reasonable, affordable and technologically practicable. It should be limited to products determined to present unreasonable risk of the occurrence of fire leading to death, injury or significant property damage.[77]

One often overlooked factor, which allows clothing fires to avoid the attention of regulation, is their personal nature. Clothing fires more usually occur to single individuals and not to groups and so tend not to draw media attention. Thus, while the effort to control burns accidents is both socially and economically worthwhile, social pressures to do so are limited. At the individual level, however for the survivors of the clothing fires, burning causes scarring both mentally and physically that even the best of modern plastic surgery cannot remove.

Lin *et al.*[78] investigated the necessity for mandatory standards and identified several influencing factors. First, the consumer may not be informed of the underlying hazard and hence, may not perceive the need for protection and secondly, the consumer who selects to live dangerously may be exposing others to the same risk. However, consumer choice is invariably influenced by cost of the material. An experiment was conducted in a ladies dress department, where some dresses with fire retardant finishes and others with conventional finish were put on sale. Women were fully advised of the safety factor, yet they invariably bought the ones with conventional finish, as they were cheaper.[79] Also, many consumers do not follow the instructions on hazards and care and therefore may be ignorant or unaware of their implications. Legislation appears to be the only way to force safety upon the consumer.[74]

2.10 CURRENT REGULATIONS AND STANDARDS

Fabric flammability regulations in different countries are similar in spirit, but they differ in words. Legislation regarding flammability of fabrics for the first time was brought in force on January 27th 1945 in California.[80] However, lack of precise definitions and a test method made the Act unenforceable.

Most of the standards are based on pass-fail criteria and does not define individual thermal properties and does not relate the thermal properties with the burn injuries. Some standard test methods with different spirits are briefly mentioned :

The US General Apparel Flammability Standard (GAFS) relies on the concept that the extent of injury appears to be more closely related to garment configuration and fit than to fibre content and fabric burn time and so incorporates garments configuration, ease of ignition and heat transfer.[81]

In contrast, Australian regulations incorporate labeling of all garments to display an appropriate hazard classification.[82] The Australian philosophy about consumer protection is to inform consumers of the hazard and hence permit them to make their own judgment as to whether the risk is acceptable.[83] AS 1176 comprise three test methods: Part 1: ease of ignition; Part 2: burning time and heat output; and Part 3: surface burning times for pile fabrics.[84]

Canadian regulation for children sleepwear dictates use of fabrics such as polyester, nylon and modacrylic for manufacturing childrens nightgowns and robes rather than cotton and wool. The probable reason is the difficulty in ignition and lower rate of flame spread in polyester and nylon fabrics.[85]

Dutch and French standards were derived from an ISO standard viz. ISO 6940 on determination of ease of ignition and ISO 6941 on measurement of flame spread properties.

The Swedish and Norwegian regulations used an American (ASTM) standard on a test method for flammability of clothing textiles. Because of the submitted report, CEN 248 Committee has been tasked with drafting an appropriate test method and standard.[86]

Most of the countries imposed legislation and targeted the textile commodity which is responsible for the lives of their people and it is found that night wears and children wears were mostly studied by them other than any garment, there exist standards and legislations for other fabrics used for various commodity, but no standards exists for testing garment used in India, and specifically the saree, even though it has a complex wearing pattern.

There exists no standard for measuring the flammable characteristics of saree, neither in India nor abroad, some of the standards recommended by different countries for apparel and consumer products are given in the Table 2.6 and Table 2.7.

Table 2.6 Commonly Practiced Testing Standards in India[87]

Country/ Organisa -tion	Standards	Scope	Application
India	IS 1187: 1996	Applicable to all types of textiles fabrics, clothing and garments- Woven, Knitted, Bonded.	Fabric is exposure for 38mm Butane/LPG gas flame for 12 second. Measured char length in cellulose.
	Method A	Laminated or Surface coating.	Duration of After glow Duration of After flash.
	IS11871: 1996 Method B		Fabric is exposure for 16mm Butane/ LPG gas flame for 1 second at 45° angle. Time required for flame to traverse 127 mm.
	IS 12467:1988	Ignitability of material combination viz. covers & fillings used in upholstered seating when subjected to Smouldering cigarette.	Fabric is exposed to 68 mm smouldering Cigarette.

Table 2.7 Commonly Practiced Testing Standards in the World[87]

Country/ Organis-ation	Standards	Scope	Application
USA	ASTMD 1230-94	Measures and describe properties of materials, products or assemblies in response to heat and flame under the laboratory Condition.	Fabric is exposure for 16mm. Butane/ LPG Flame for 1 second at 45.° Time required for flame to traverse127 mm. Brushing required for raised fibre surface. Dry-cleaning, laundering required for Flame retardant treated fabric.
	ASTM D 3659-80	Simulates the burning characteristics of a Vertically hanging Garment supported at the shoulders, Hanging away from the body & Ignited at the lower edge.	Methane gas (97% pure) flame. Weight loss is measured.
	Method 5905, 108-GP-IP	Flame resistance of material. Rate of burning of consumer type textiles.(Vertical strip test)	Char length. Time for the flame to travel 25 inches.
UK	BS 5438:1976 Test 1 Test 2 Test 3	Measuring the aspect of flammability of vertically oriented textiles fabrics either in single layer or in assembly of two or more layers.	Time of exposure not specified but exposed up to 8 second or till the specimen catches the fire, whichever is minimum. Flame height is 45±2 mm is applied on Face of vertical fabric. Minimum time of ignition is measured.
	BS 2963:1958 Method A (Vertical strip Test)	Applied to all types of Construction, Flat sheet, and cutting fabrics.	Fabric is exposure for 40 mm gas Flame for 12 second. Flame resistance rating is reported.
	BS 2963:1958 Method B (Inclined test)		Fabric is exposure for 16mm gas flame for time required for flame to traverse 127 mm.
ISO	ISO 6940	Flammability of vertically oriented fabric intended of apparels, curtains and draperies, in the form of single/ multi-component sandwich.	Reported mean ignition time. Source: commercial grade propane or butane gas.
	ISO 6941-84	Flammability of vertically oriented intended of apparels, curtains & drapers,in the form of single or multi-component sandwich.	Flame height 40 + 2 mm Source: commercial grade propane or butane gas exposed for 5 to 15 seconds.
German	DIN 54 331	Determination of the burning behaviour of combustible textiles-Semi-circle tester.	Propane flame 90° angle of burning in 15 second. After glow.