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Possible Fire and Electric Shock Hazards from Hot Lamps in Miniature Christmas Tree Light Strings and Decorations

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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, *Secretary*
Jordan J. Baruch, *Assistant Secretary for Science and Technology*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

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INTRODUCTION

Upon cursory examination, miniature or midget Christmas tree light strings appear to be innocuous. The total power consumption of these series-connected sets is considerably lower than that of parallel-connected light strings, and the miniature lamps seem to operate at lower temperatures. However, there are several technical subtleties in series type light string construction and operation which, under certain conditions of use or predictable misuse, can lead to extremely high lamp bulb surface temperatures. These high temperatures, in turn, can cause subsequent ignition (fire) and/or electric shock hazards [(1)]. The technical subtleties and conditions of use or misuse are discussed in this report, along with a description of laboratory testing which documents the potential fire and shock hazards.

The work upon which this report is based was funded by the Consumer Product Safety Commission (CPSC) as part of their Regulatory Development program. The CPSC had determined that voluntary standards for series constructed miniature Christmas tree lights and lighted decorations did not adequately address existing hazards. Furthermore, some light strings on the market did not meet any recognized safety standard. The Commission therefore acted to have an offeror develop a safety standard for subsequent promulgation as a mandatory rule. The author of this report served as technical advisor to the CPSC throughout the standards development process.

PRODUCT DESCRIPTION

The lamps of a miniature Christmas tree light string or decoration are electrically connected in series. The ends of the series circuit are terminated in an attachment plug, by means of which 120 V ac is applied across the string when the plug is inserted into a household receptacle. Sometimes two or more series strings are electrically connected in parallel to a common attachment plug, but the total package is still referred to as a "light string" or "light set." The total current drawn by a series string flows through each lamp in the string and is determined by the total

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(1) Fire and electric shock hazards can also result from short circuits (such as caused by staples inserted through the wire) or from poor light string construction (bare wires exposed, etc). Overcurrent protective devices and improved methods of light string construction provide relatively easy and effective solutions to these problems. This report will mainly concern those hazards resulting from high lamp bulb surface temperature - a more difficult problem to address.

resistance of all the lamp filaments in the string. The voltage developed across each lamp is a function of the number of lamps in the series string. The more lamps there are in series, the less will be the voltage developed across each lamp.

If a lamp is removed from a series string, none of the remaining lamps in that string can operate. Lamp burn-out would produce the same effect were it not for the fact that a shunting device is generally built into each lamp bulb envelope. The shunt is electrically isolated unless the lamp filament should open: the shunting device is then activated by the voltage surge, thereby bypassing the filament and allowing the remaining lamps in the string to continue operating.

Physically, a miniature Christmas tree light string consists of a number of lampholders, or sockets, connected by wires in series to an attachment plug. Typically, each lamp of a miniature Christmas tree light set is fitted into a lamp base, with the two lamp leads protruding through the base and extending upward along opposite sides. When the lamp base is inserted into a lampholder; the protruding lamp leads make contact with terminals contained within the lampholder (see figure 1).

A burned out lamp can be replaced by removing the lamp-lamp base assembly from the lampholder and either (1) replacing it with a similar lamp-lamp base assembly, or (2) separating the lamp bulb from the lamp base, inserting a new lamp bulb into the original base, then replacing the entire assembly into the lampholder. The latter method is likely to be used if the replacement lamp is supplied without a base or if the supplied base does not fit into the light string being repaired.

NORMAL OPERATING CONDITIONS

Normally operating miniature Christmas tree lamps dissipate anywhere from 1/3 to 1 1/3 watts. Hot spot surface temperatures range between 35°C and 190°C depending upon dissipation and filament placement within the glass bulb. If the filament is centered, normal surface temperatures rarely exceed 90°C. Some lighted decorations use miniature lamps which dissipate up to 2 watts and produce surface temperatures up to 270°C if the filament is touching the glass envelope. As a rule, the lamps in these decorations are rigidly held in place.

Temperatures even as high as 270°C are not sufficient to cause ignition of materials. However, temperatures over 110°C can cause melting of some lampholder materials, and may subsequently expose electrically live parts if certain other conditions are present. These conditions include the contact of a hot lamp with another part of the same or different light string, or the placing of a decorative attachment over the hot lamp such that the generated heat cannot readily escape. This subject will be discussed in more detail later.

VARIATION FROM NORMAL OPERATING CONDITIONS

Under certain conditions, miniature Christmas tree lamp power dissipation can increase dramatically. Subsequent lamp hot spot surface temperature can then rise to levels sufficient for the lamp to cause ignition of a Christmas tree or other materials, such as decorative cotton, tissue paper, newspaper, etc., with which it may come into contact. There are two basic sets of circumstances which can cause such excessive power dissipation by the miniature lamps: one can be initiated by not promptly replacing burned out lamps; the other can be initiated by placing lamps into a light string for which they were not designed.

Variation Caused by Not Promptly Replacing Burned Out Lamps - Cascade Failure

As noted previously, a shunt contained within the miniature Christmas tree lamp is activated when the lamp filament opens, allowing current to continue flowing through the string and the remaining lamps to remain lighted. However, the current through the string increases slightly when the shunt is activated since the shunt resistance is lower than the filament resistance. If two or three lamps burn out before any are replaced, the current increase can become significant. Furthermore, as the remaining lamps pass the increased current, this tends to reduce their life. As more lamps burn out, further increases in current result, with the time between current increases and further burnouts becoming increasingly shorter. During this time the remaining lamps can dissipate considerable power before they too eventually open.

One defense against the type of cascade failure just described is to include an overcurrent protective device in the light string series circuit: this opens the circuit after the current increases above a specified value. However, most inexpensive devices of this nature rely on heat generated by high current flow to open a fusing device. For the device to open fast enough to prevent damage from high hot spot lamp surface temperatures, a current increase from normal to twice normal is generally required. Unfortunately, certain lamps can develop hazardous surface temperatures at currents considerably less than twice their normal current. Even if light string design were such that an overcurrent protective device could prevent high lamp surface temperatures in a cascade failure situation, additional means of protection should be considered for handling those situations where the protective device either fails to operate or can easily be defeated by the consumer.

Variation Caused by Placing Lamps Into a Light Set for Which They Were Not Designed

High lamp dissipation can also result if a consumer should deliberately or inadvertently insert into a light string one or more lamps which are not designed for that string. As discussed earlier, light strings with relatively few lamps in series necessarily drop more voltage across each lamp in the string than do light strings with a larger number of lamps in series. A series string of 50 lamps requires lamps designed for approximately 2.4 volts (50 times 2.4 volts equals the 120 V ac household voltage), whereas a series string of 10 lamps requires lamps designed for 12 volts. To complicate matters further, some 50 light sets use 2.4 volt lamps, while others use 12 volt lamps. (In the latter case the 50 light set is comprised of five parallel strings, with 10 lamps in series in each string.) A 35 light set may contain either 3.5 volt lamps (35 lights in series) or 7 volt lamps (two parallel strings of 17 and 18 lamps in series, respectively).

In the above situations, there is a problem in assuring that the proper replacement lamps are used in a given string - particularly if the consumer owns more than one type of light set. Lamps are physically interchangeable from one string to another. Replacement lamps (either those which accompany the light string or which may be purchased separately) are often not furnished with bases: the consumer simply removes the burned out lamp from its base and inserts a fresh lamp in the same base. This concept has practical advantages as noted below, but allows <u>any</u> lamp to be put into any light string, regardless of design. Furthermore, lamp and lamp base combinations can sometimes be interchanged as a unit between light sets since (1) many lampholders are sufficiently similar in design that they will accept lamp-lamp base assemblies of different manufacture, and (2) different light strings from the same manufacturer typically all use the same style of lampholder.

Small lamp size combined with appearance considerations have, to date, prevented any meaningful method of identifying the lamp itself. Coding of the lamp base is possible, but would require that lamps be cemented into their bases. This would complicate the replacement lamp market and could make it difficult for the consumer to find a lamp to fit his string unless all manufacturers agreed on a standard lampholder configuration. The latter is unlikely because of the considerable monetary loss to those manufacturers who would have to change their lampholder and lamp base dies. (As discussed above, present replacement lamps are typically sold without bases.) Difficulty in locating a replacement lamp is itself a safety hazard, since cascade failure can result if burned-out lamps are not replaced.

Light string current is dependent on the total filament resistance in the string: a lower total resistance results in a higher current flow. To keep lamp brightness (which is a function of lamp power dissipation) roughly equivalent between strings with different numbers of lights, the lower voltage lamps are designed to operate at higher current than are the higher voltage lamps. Since power dissipation is the product of voltage and current, the greater current drawn by lower voltage lamps tends to bring their power dissipation, and hence their light output, up to the same general range as the higher voltage, lower current lamps [2].

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(2) The balance is not perfect. The lamps in a string with only 10 lights in series burn perceptibly brighter (and will generally dissipate two to three times more power) than the lamps in strings with 50 lights in series.

The actual current drawn by any series string depends on the manufacturer's design and on variations in filament resistance from one lamp to another. Strings with only 10 lamps in series (high voltage lamps) usually draw from 85 to 100 mA, whereas strings with 17 to 50 lamps in series (lower voltage lamps) draw 125 to 150 mA or more. Some light strings manufactured in Italy draw over 200 mA.

If a few high voltage lamps are placed in a string designed for lower voltage lamps, the high voltage lamps will be subjected to the higher current that is characteristic of strings using low voltage lamps, and hence will operate much brighter and hotter than normal. An overcurrent protective device is of no help in this situation because the higher filament resistance of the substituted lamps actually lowers string current slightly. Large reductions in current do not occur because the added resistance of the high voltage lamp or lamps is only a small portion of the total series circuit resistance.

BASIC HAZARDS

Fire and electric shock are two basic hazards that can result from overheated miniature Christmas tree lamps. Fire can result if the lamp surface temperature becomes high enough to ignite materials which may come into contact with the lamp. Electric shock can result if the lamp surface temperature becomes hot enough to melt insulating material with which it may come into contact, and if electrically live parts are subsequently exposed and touched by a consumer.

ELECTRIC SHOCK HAZARD

An electric shock hazard [3] can develop from insulation melting caused by high lamp surface temperatures. This hazard can occur even with normally operating light strings because the normal operating hot spot

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[3] A shock hazard results even if exposed conducting parts happen to be in the middle of the series circuit. Currents of 80 to 150 mA are common for series-constructed light strings. Total resistance of the series string can therefore be calculated by Ohm's Law to be between 800 and 1500 ohms (120 V ac/150 mA = 800 ohms and 120 V ac/80 mA = 1,500 ohms). A value of 1500 ohms is commonly used to represent electrical resistance of the human body between perspiring or damp hands. This information and further calculations using Ohm's Law show that currents in the range of 40 to 52 mA can flow through the body of a person even though contact with exposed conducting parts is made at a string location which results in minimum current flow. Current flow of 5 mA through the human body commonly causes involuntary muscle contraction. Currents in excess of 18 mA normally contract the chest muscles, so that breathing is stopped during the shock. Currents in excess of 50 mA can cause ventricular fibrillation and subsequent death if the fibrillation is not stopped.

surface temperature of certain lamps, particularly if a lamp filament is off center, is higher than the melting temperature of some plastic insulating materials.

As stated earlier, hot spot surface temperatures for normally operating miniature Christmas tree lamps range between 35°C and 190°C, depending upon lamp dissipation and filament placement relative to the bulb envelope. Temperatures over 175°C are unusual, however. The melting temperature for one of the more popular lampholder materials, polyethylene, is between 110 and 140°C 1/, depending on the density of the material. Another popular lampholder material, polypropylene, has a melting temperature which ranges between 160 and 175°C 2/, making it safer than polyethylene. The melting temperature of a third popular lampholder material, polyvinyl chloride (PVC), depends upon the amount of plasticizers and other materials added to give characteristics desired of the finished product. (Pure PVC is rigid, hence, plasticizers are added to increase flexibility.) The melting temperature of PVC can, therefore, vary between 110 and 180°C, but the type most often used for lampholders in miniature Christmas tree light strings has a melting temperature between 160 and 175°C - similar to polypropylene.

Under conditions of high ambient temperature, a lampholder may show some slight deformation before the actual melting temperature is reached. This is due to stress relaxation in the plastic at its mold release temperature. A lampholder is normally manufactured by heating the plastic material above its melting temperature and then molding it to the desired shape. Following this, the plastic is cooled to a temperature below its melting temperature and released from the mold. Should the lampholder again be subjected to the mold release temperature, stresses which may have built up in the molding process could cause some deformation. Because of processing economics, the temperature of the plastic when released from the mold is as close as possible to the melting temperature, the two temperatures perhaps separated by as little as 10°C.

Exposure of Conducting Parts Due to Contact Between a Hot Lamp and Another Lampholder

A hot miniature Christmas tree lamp may not always come in contact with another portion of the same or another light string or decoration, but the likelihood of such contact may be quite high. Some lighted decorations are designed with such close light spacing that contact between one lamp and another lampholder is almost inevitable. Contact may also occur because a portion of a light string becomes dislodged from its intended decorative position and falls against either another portion of the same string or against a separate string. Furthermore, consumers are wont to exercise considerable ingenuity in designing new and spectacular effects with light strings and other decorations.

In 1977, a major manufacturer packaged miniature Christmas light strings with the lamps bunched together inside a plastic cup. When energized for display purposes, the closely spaced lights shining out the top of the cup presented an unusual effect. No hazard resulted because the plastic insulating materials had a high melting temperature. However, a consumer might be inspired by this type of display and decide to try a similar decorating scheme with his own light string, perhaps one with less safe plastic insulating materials.

In the laboratory, a normally operating 35 light, two-way string (i.e., two series circuits in parallel, one of 17 lamps and the other of 18) was inserted into a large ceramic coffee mug to achieve a decorative effect. The visual appearance was striking; unfortunately, not all of the lamps emerged above the top of the mug. Some lamps became entangled in the wires below when the lights were inserted into the mug. After approximately 30 minutes, the normal operating temperature on a few of these entangled lamps, combined with lack of adequate air flow, caused the insulation material of surrounding lampholders to melt. One lampholder melted sufficiently for its lamp to fall out of the holder and open that portion of the string. However, the other portion of the string continued operating.

After two hours, the set was unplugged and removed from the coffee mug. The light string was found to have numerous exposed conducting parts (see figure 2) and would have presented a serious shock hazard had it not been unplugged before removal from the mug.

Exposure of Conducting Parts in Non-Contact Situations

Contact between a hot lamp and light string insulating material is not the only prerequisite for development of an electric shock hazard. Figure 3 shows lampholder melting which occurred when a close-fitting decorative attachment [(4)] was placed over the lamp assembly (lamp, lamp base and lampholder); figure 4 shows the decorative attachment used. The lamp assembly was positioned vertically with the lamp pointing down. Air movement through the attachment was restricted, as might happen if cotton, artificial snow or other decorative material were used on the Christmas tree.

[(4)] A decorative attachment is a device designed to fit over either the lamp bulb or the complete lamp assembly of a light string and provide a lighted display of some sort. Decorative attachments are sometimes supplied as part of a light set, but can also be purchased separately. They are removable (so that burned out lamps can be replaced) and can, therefore, be moved from one light string to another to enhance an overall decorative effect.

The melting occurred under simulated conditions [5] with a 12 volt lamp operated in a light string designed for lower voltage lamps. The current through the lamp, and hence the voltage across the lamp, were much higher than normal for that lamp, but not for the light string into which it was inserted. In this test, the 12 volt lamp passed 161 mA and dissipated 4.5 watts for 10 minutes. The current was then increased by 6 mA to simulate burn out of another lamp somewhere in the series string: for the next 11 minutes the lamp passed 167 mA and dissipated 5.5 watts. At the end of that period the lamp filament ceased operation. The melting temperature of the lampholder material used for the test ranges between 110 and 130°C.

Four other lamp assemblies were tested under similar conditions and with the same lampholder material. Although considerable melting was observed (see figure 5), no electrical conducting parts were exposed. The evidence suggests, however, that a potential problem exists for certain types of lampholder materials. In contrast to these test results, tests of lamp assemblies in which the lampholder was molded from higher melting point materials show no such extreme deformations (see figure 6).

Melting similar to that shown in figures 3 and 5 may also result if the lamp filament is located close to the base of the bulb. Heat from such a filament location can be sufficient to cause deformation of low melting point lampholder materials, even without the presence of a close fitting decorative attachment. Typical lamp surface temperatures at locations next to the lamp base are plotted in figure 7 as a function of lamp dissipation and filament distance from the base [6].

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[5] A slide wire rheostat is connected in series with the lamp under test and the 120 V ac supply (see figure 8). The rheostat simulates the total resistance of other lamps in the string, thereby eliminating testing problems caused by random failures or poor contacts in these other lamps. The simulation current is determined by inserting the lamp to be tested in an actual light string, then measuring the current flow in that string. The slide wire rheostat of the simulated circuit is then adjusted to provide the predetermined current flow through the lamp under test. Decrease of the rheostat resistance from the established value simulates the increase in current which results when one or more lamps burn out. This new value of current can also be determined beforehand by trial with an actual light string, if desired.

[6] The data for this figure was obtained in a manner similar to that described under Detailed Test Descriptions and Test Results in the section on Fire Hazards.

As discussed earlier, consumer actions (or inactions), such as failure to replace burned out lamps or replacement with lamps of incorrect voltage rating, can aggravate a situation and cause lamp power dissipation to rise considerably above normal. Lamps which usually dissipate 1 watt may thus dissipate 4 or 5 watts or more. As seen from figure 7, lamp dissipation of 4 1/2 watts produces temperatures at the base of the lamp in the range of 130 to 205°C. The upper range of these temperatures is high enough to cause melting sufficient to expose the conducting parts of a lamp's own lampholder if low temperature (110-120°C) plastic insulating material has been used.

FIRE HAZARD

Series constructed miniature Christmas tree light strings and decorations present a potential fire hazard if lamp surface temperatures become high enough to ignite materials which may come into contact with the lamps. Even though there is difficulty in pinpointing the exact cause of fires related to decorative Christmas material (because the evidence is usually damaged or destroyed by the fire), enough evidence has been gathered to show that miniature Christmas light strings and decorations have been the cause of at least some fires 3/. To reduce the risk of fire from these strings, detailed information on the parameters affecting ignition must be obtained. From this information, one or more hazard intervention mechanisms can be introduced into the design, manufacture and/or use of the strings.

The following section gives a brief description of the laboratory test methodology used to determine if and when ignition can occur from a hot miniature Christmas lamp. This is followed by a section which gives more detailed information on the actual tests and their results.

Test Methodology

Most of the data in the literature concerning ignition temperatures is based on experiments with heat sources much larger in size than miniature Christmas tree lamps. In many cases the surface temperature of a miniature lamp is found to exceed the published ignition temperatures of materials often found in the vicinity of light strings (e.g., dry pine needles, wrapping paper, tissue paper, decorative cotton, newspaper, etc.). Additional testing was therefore conducted to determine whether a hot miniature lamp could indeed ignite typical materials and, if so, at what temperatures.

Whether any specific material will ignite upon contact with a hot miniature Christmas tree lamp depends upon: (1) oxygen availability, (2) the surface temperature of the lamp, (3) the duration of contact, (4) the heat flow from the lamp to the material and (5) the material sample size.

For a given set of material characteristics and oxygen availability, the overriding factor is surface temperature of the lamp. Unless this temperature is above some minimum value, there will be no ignition despite extended contact times or increased heat flows. At surface temperatures higher than the minimum required, the contact time necessary to cause ignition for a given heat flow will, of course, decrease.

Heat flow is a function of lamp power dissipation and bulb geometry. Since its value normally increases linearly with surface temperature, and since bulb geometry is similar for almost all lamps, a determination of actual heat flow is necessary only if the simulation of a miniature Christmas lamp is required for ignition testing.

Testing for ignition cannot readily be accomplished by utilizing an operating light string. A number of events can intercede, either before the surface temperature of a particular lamp becomes sufficiently high to cause ignition of materials with which it may be in contact, or before sufficient contact time has elapsed. These events include: (1) the lamp filament may open, (2) the lamp shunt may be activated by the abnormal heat and voltage drop in the lamp and thereby bypass the filament, (3) the filaments and/or shunts of other lamps in the series string may open thereby affecting the operating time of the lamp in question, or (4) lampholder material may melt and cause loss of electrical contact in one or more lamps in the series string, thereby preventing current flow through the lamp under test.

Because of the above listed factors, a test of 100, or even 1,000, light strings might not result in a single ignition. However, 40 to 50 million series-connected miniature Christmas light strings and decorations are sold each year. If conditions were such that only one set in 10,000 were capable of causing a fire, there would still be the possibility for 4,000 to 5,000 fires each year just among the new sets sold. If only 1% of these possibilities resulted in an actual fire, there would be 40 to 50 fires each year due to miniature Christmas lights.

The previously described difficulty of testing for ignition with an operating Christmas tree light string dictated that initial tests be made utilizing a simulation. This was accomplished by using a soldering iron covered with a borasilicate glass sleeve to simulate a hot miniature Christmas tree lamp.

To achieve the simulation, temperatures on the surface of typical miniature Christmas tree lamps were first determined as a function of lamp dissipation and filament placement relative to the lamp envelope. The soldering iron was then plugged into a variable alternating current supply and the supply adjusted to provide the indicated temperatures on the glass sleeve. Slug calorimeter measurements were performed at different surface temperatures on both the soldering iron simulator and various hot lamps to verify that heat flow from each was essentially the same (although small differences can be compensated for by changing exposure time). Ignition tests were then performed using the simulator. These tests consisted of bringing various material samples into contact with the simulator at increasing simulator surface temperatures, recording the duration of contact, and noting whether or not either glowing or flaming ignition resulted.

As a further check on the validity of the simulator measurements, ignition tests were later attempted on operating hot miniature Christmas tree lamps. To circumvent some of the difficulties in using a complete string, the lamps were tested individually. The problems of premature lamp filament burn out or shunt activation remained, however. Lamp current and voltage were set by means of a slide wire rheostat in series with the lamp and the 120 V ac supply. The current and voltage were set to values which had been predetermined from actual operating conditions. Subsequent glowing ignitions caused by some of the hot miniature Christmas tree lamps tested were recorded on video tape.

Lamp filament life was not sufficiently long for surface temperature measurements to be made during the ignition testing utilizing actual miniature Christmas lamps, but power dissipation just prior to ignition was recorded. From the previously determined data relating typical lamp surface temperatures to lamp power dissipation and filament placement, the approximate lamp surface temperature at glowing ignition could be determined and compared to the surface temperatures at which glowing and flaming ignition occurred for similar materials and times of exposure when using the soldering iron simulator. Comparison of the data shows that there is substantial agreement. A discussion of the tests and their results follows.

Detailed Test Descriptions and Test Results

(a) Determination of typical lamp surface temperatures as a function of lamp power dissipation and filament placement

The initial laboratory tests were designed to determine typical lamp hot spot surface temperature as a function of both lamp power dissipation and lamp filament placement relative to the glass envelope. Measurements were made on lamps of various types and from various manufacturers. Filament placement was determined visually with the lamp operating at less than normal power. Each lamp tested was subjected to increasing wattage dissipation by means of the test set up shown in figure 8. Maximum temperature on the bulb surface was determined by hand-shifting the location of a chromel-alumel thermocouple connected to a digital thermometer which had an accuracy of better than 1 $^{\circ}$C. The thermocouple bead was approximately 0.8 mm in diameter. At each new wattage setting the surface temperature was allowed to stabilize for at least two minutes before a reading was taken. Longer times were allowed whenever possible, but if too much time was utilized in lower power measurements, then either the lamp filament would open or the shunt would activate prematurely - either condition precluding further measurements on that particular lamp.

The data are plotted in figure 9. Data were taken for many more lamps than are shown in the figure, but only the extremes of filament placement are plotted. The solid lines indicate lamps in which the filament was touching the glass envelope; the dotted lines indicate lamps in which the filament was centered. Curves representing all other filament placements fall within the general envelope defined by the curves shown. Also, for simplicity, not every curve representing lamps with the two extremes of filament placement has been plotted. The curves shown here are those which typify the observed spread [(7)].

Because of the relatively short temperature stabilization times utilized in obtaining the data plotted in figure 9, the recorded temperatures may be somewhat lower than they might have been had longer stabilization times been possible. To check this out, single point measurements (i.e., increasing the lamp wattage immediately to a specific value and measuring surface temperature only at that wattage) were performed on several lamps. This procedure permitted much longer temperature stabilization times, but did not allow a complete curve for any one lamp to be plotted. The data points obtained in this manner could, however, be compared (for lamps of similar type) with those used in plotting the curves of figure 9. In every case, the single point data fell within the range of the corresponding complete curves.

The lamp current measured just before the lamp filament ceased to operate is indicated at the high end of each curve plotted in figure 9. This current value is an indication of how likely a lamp might dissipate the maximum wattage shown on the curve, either in the string for which it was designed or in another string into which it might be placed. For example, one of the curves for an E-12 lamp indicates that a current of 155 mA was passing through the lamp at its maximum recorded dissipation of 4.9 watts. The corresponding hot spot surface temperature was 465°C. Since normal current for certain types of presently available light strings is around 150 mA, and since some light strings manufactured in Italy normally draw over 200 mA, there is a high probability that the E-12 lamp might experience 155 mA if inserted into the wrong light string, and hence dissipate 4.9 watts.

The lamp current indicated at the high end of each curve is also useful for determining the likelihood that an overcurrent protective device would avert the high lamp surface temperature which results at that current. In the foregoing example, the value of 155 mA is only 1.7 times

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[(7)] Filament shape and orientation may also have some effect on the curves. Unfortunately, any such effect could not be determined from the data collected because practically all lamps currently manufactured have similar filament shape and orientation. One notable exception is a lamp with a longer, vertically mounted filament. Curves plotted from the limited data available for lamps with this filament type show that lamp surface temperature tends to be lower for a given wattage dissipation and filament placement. Further investigation is necessary.

higher than the normal current for the 10 light series string in which the E-12 lamp is designed to operate. Since most overcurrent protective devices are not designed to work reliably over short time intervals until the overcurrent approaches twice the normal value, the presence of such a device in the string is not likely to avert a high lamp surface temperature. Furthermore, if the E-12 lamp were inserted into a string which normally draws 150 mA, an overcurrent protective device in that string would be useless in preventing high surface temperatures on the lamps.

(b) Simulation of a miniature Christmas tree lamp

After typical lamp bulb surface temperatures were documented, the next step involved development of a simulated miniature Christmas tree lamp which would not have unpredictable filament burn-out problems. This was achieved by means of a soldering iron (specifically an Ungar type 6100 iron with a type 6200 45 watt heat cartridge) that was fitted with a glass sleeve (by placing a 10 mm ID, 12 mm OD borosilicate test tube over the 10 mm OD body of the heat cartridge). A hot spot on the heat cartridge was used in the simulations.

The specific soldering iron used in the simulation is noted to enable exact duplication of the test if desired. However, any soldering iron of similar or smaller dimensions that can generate temperatures up to 550°C on its surface could be used for the simulation with the results being essentially the same.

The soldering iron was supplied from two Variacs (variable voltage alternating current supplies) connected in series. An ac line regulator, adjusted to 120 V ac, furnished the input to the first Variac. The output of the first Variac was set to 140 V ac and supplied the input to the second Variac. The output of this Variac supplied the soldering iron and was adjusted to obtain the desired surface temperature at the hot spot on the glass sleeve surrounding the heat cartridge. Output from the second Variac ranged between 110 V ac for surface temperatures in the range 390-420°C and 155 V ac for surface temperatures in the range 530-550°C.

Smaller diameter soldering irons were investigated as simulators, but surface temperature above 450°C could not be achieved with any of the smaller diameter irons available.

(c) Ignition testing using simulator

Once the simulator was devised, a series of ignition attempts were conducted. Each ignition attempt consisted of bringing an edge of the material under test into contact with the previously determined hot spot on the glass covered heat cartridge. At least ten attempts were made for each material at each temperature listed in table 1. If two significantly different results were obtained for a material/temperature combination, both results are listed with the corresponding percentage of attempts to which each applies shown in parentheses; absence of such percentages indicates uniform results in all trials of the given type. Prior to and following each series of ignition attempts, the hot spot surface temperature was measured by means of the same chromel-alumel thermocouple and digital thermometer as used in the lamp surface temperature measurements.

The method of applying the material under test to the heat source was adapted to the type of material and the temperature of the simulator hot spot. In some instances, the material and temperature were such that a single layer of the sample did not provide a sufficient concentration of flammable material to result in ignition before the material was consumed and contact with the hot spot terminated. To counteract this, the material was folded and applied to the heat source in layers. Layered application tends to reduce oxygen availability while the sample is in contact with the heat source, however. Under these conditions, the flaming type of ignition often did not take place until the sample was removed from the heat source. Layered application was used occasionally for newspaper, tissue paper, wrapping paper and cheesecloth, but not for the cotton dress or the cardboard.

The results in table 1 show untreated absorbent cotton to be the most flammable of the materials tested, with tissue paper, cheesecloth and the cotton dress from a doll shaped Christmas light string decorative attachment almost as flammable. Dry pine needles were not available for testing. Temperatures of approximately 450°C caused glowing ignition after 10 to 30 seconds for absorbent cotton, newspaper, tissue paper, cheesecloth, newspaper, and the decorative attachment doll dress. Flaming ignition was observed for the absorbent cotton at slightly longer exposure times at the same temperature. According to the curves of figure 9, a hot spot lamp surface temperature of 450°C can result from lamp power dissipations of 4.5 to 6.5 watts depending upon filament location.

(d) Ignition testing using miniature Christmas tree lamps

Following the ignition testing utilizing a simulated miniature Christmas tree lamp, an effort was made to achieve ignition from actual miniature Christmas tree lamps. The lamp for each trial was inserted into the test circuit of figure 8. An edge of the material under test was placed in contact with the lamp surface hot spot (previously determined by thermocouple measurement at normal lamp power dissipation). Resistance of the slide wire rheostat was decreased until the power dissipated by the lamp approached the 6 watt range. Voltage across the lamp and current through the lamp were then recorded. A glowing ignition was observed in a majority of those instances in which the lamp filament continued to operate for longer than 2 to 3 minutes. The longer operating time allowed the lamp hot spot surface temperature to reach a maximum value. The glowing ignition observations were recorded on video tape.

Approximately 50 lamps of the 12 volt variety from two different manufacturers, were tested. These lamps were selected for testing because previous screening had shown that the filament of at least some samples would continue operating beyond two minutes at 6 watts dissipation. Seven lamps produced glowing ignition in either the cotton doll dress or sections of untreated absorbent cotton. For these seven lamps, table 2 provides information concerning lamp type, filament placement, time to ignition and lamp power dissipation at ignition. Since the other lamps ceased to operate in less time than that required by the slowest of the seven to cause ignition, no definitive information about their ignition potential could be gained.

The tested lamps were of the type commonly used in steady burning or synchronous flasher light sets. They are not "ballast" lamps [8] - a type which might be expected to produce even more alarming results.

The absence of flaming ignition in any of the tests utilizing actual miniature Christmas lamps does not indicate that flaming ignition is impossible. Rather, it shows only that the maximum surface temperatures attained on these particular lamps were not sufficiently high to cause it. Although lamp life was too short for surface temperatures to be measured during the ignition testing, the effective temperature can be deduced from the lamp filament location and from the maximum lamp power dissipation (see table 2) recorded at the time the filament ceased to operate. This information and the use of figure 9 (which relates lamp surface temperature to lamp dissipation and filament placement), yields the maximum range of temperatures to which the surface of the lamp could rise, given sufficient operating time. The actual temperatures attained may have been somewhat lower. The maximum surface temperature range as determined for the seven lamps which caused glowing ignition (see table 2) is between 425 and 475 $^{\circ}$C. As indicated by the ignition tests with the soldering iron simulator (see table 1), these temperatures are in a range for producing glowing ignition on the decorative attachment doll dress, but are not sufficiently high for flaming ignition.

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(8) The type of lamp known as a "ballast" lamp is used in light sets where lamps twinkle on and off independently of one another. These sets differ from synchronous flasher sets in which the on-and-off is controlled by a single flasher lamp which opens or closes the entire series string at the same instant. When a light set contains lamps with independent flasher controls, at least some of the lamps in the series string must remain on at all times to prevent random sharp rises in current which could burn out all the lamps at once. The lamps which remain on continuously, called "ballast" lamps, must have relatively strong filaments in order to absorb many current surges throughout their life. Prescreening of "ballast" type lamps showed that some may operate for 20 minutes or longer when dissipating 6 watts.

The contact times before ignition are somewhat longer for the tested lamps (15-90 sec; from table 2) than they are for the soldering iron simulator (4-20 sec; from table 1). This results, in part, from the necessity to counteract short lamp life at higher power levels by initiating contact with a lamp before its surface temperature has reached a maximum value.

When checked again at the completion of the ignition tests, some tested lamps, surprisingly, still contained an operable filament: the lamp shunts had apparently been temporarily activated by the elevated voltage and interior bulb temperature levels. Activation of the shunt would bypass the lamp filament and give the same observable effect as an open filament. Once the lamp had cooled after testing, subsequent trial revealed the shunt to be inactive as the lamps again lighted.

A typical lamp shunt simply consists of three or four turns of #40 aluminum wire wound around the pair of filament support pins. The aluminum oxide coating the wire acts as an insulator, hence the current normally flows through the filament. However, if sufficient voltage is developed across the filament, the oxide coating is broken and the shunt is activated, thereby shorting the filament. High ambient temperature may also contribute to breaking through the oxide coating. Further investigation of this phenomenon is justified since little is known about the mechanics and predictability of shunt operation at higher power levels. If shunts in other lamps tested had not acted to bypass the filament, and hence reduce surface temperature, when they did, those lamps might also have caused glowing, or even possibly flaming, ignitions.

(e) Measurement of heat flow

Heat flow was measured from both the soldering iron simulator and the miniature Christmas tree lamps to determine comparability: an exact match is not necessary since exposure time can be varied to compensate for small differences. The units of heat flow (or heat flux) are calories per second per centimeter squared.

The measurements were performed with a slug calorimeter. Two 0.64 cm (1/4 inch) diameter rods of 99.99% pure copper were machined at one end, one to fit against the soldering iron simulator and the other to fit against the lamp bulbs. A thermocouple was inserted into a small hole drilled into the back of each copper slug with thermal contact maintained by a silicon heat sink compound. Each copper slug was supported in a small section of high temperature resistant elastomer. The elastomer, in turn, was held by a clamp which was secured to a ring stand. The clamp, elastomer, and appropriate copper slug assembly could be rotated and moved down the ring stand to contact the soldering iron simulator or the lamp bulb.

Thermocouple readings were begun at the moment of contact between the copper slug and either the soldering iron or lamp. The readings were continued until a plot of temperature vs. time became non-linear. The heat flux could then be calculated by means of the following equation:

$$Q = \frac{MCp}{A_f} \cdot \frac{dT}{dt}$$

where Q = heat flux in calories/sec/cm^2

M = mass of copper slug in grams

Cp = specific heat of copper, which is .0922 cal/gm/^oC

A_f = face area of the copper slug in cm^2

$\frac{dT}{dt}$ = initial linear slope of the temperature-time curve in ^oC/sec

Initial data for the lamp were taken using a shiny faced slug. Since the shiny face tends not to register radiant heat flow, additional measurements were performed using a slug darkened on the face end with India ink.

Heat flux is plotted as a function of surface temperature in figure 10 for both the soldering iron simulator and the miniature Christmas tree lamps. Since the lamps exhibit limited operating life at power dissipations necessary to produce the higher surface temperatures, several lamps were used to obtain data in this range.

The difference between the heat flux generated by the soldering iron simulator and that generated by the miniature lamps for a given surface temperature is not significant. Figure 10 shows an approximate 1.3 to 1 ratio in favor of the simulator, which can easily be compensated for by increased contact time with the lamps.

RECOMMENDED HAZARD INTERVENTION MECHANISMS

The fire hazard from overheated miniature Christmas tree light strings and decorations could be reduced considerably, and perhaps eliminated entirely, by requiring that all miniature Christmas tree lamps meet a maximum wattage/time specification. If lamps are unable to operate at some specified maximum power dissipation for more than a few minutes, lamp surface temperatures sufficiently high to ignite materials cannot be realized. The maximum wattage could be specified as a function of both (1) lamp diameter at the filament location and (2) overall lamp surface area. Larger filament-to-lamp envelope distances and larger lamp bulb surface areas permit a higher wattage to be dissipated for a given length of time before lamp surface temperatures reach the critical range [9].

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(9) Certain types of lamps with long vertically mounted filaments may also be able to dissipate more power for a given surface temperature rise, but further investigation of this is required.

For the sizes of miniature Christmas tree lamps now available, maximum power should be limited to 5 or 5 1/2 watts over a period of approximately 2 minutes. Most lower voltage lamps already conform to this kind of limitation.

It should be noted that if an upper limit on the allowable power dissipation of the lamp is set, the corresponding lifetime of the lamp must also be taken into consideration. If the former is set too low the designed operating lifetime may be too short [10] thereby giving rise to premature failure and the concomitant hazards of cascade failure or,

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[10] Other factors being equal, lamp life varies inversely as the twelfth power of the voltage at which it is operated. This can be expressed in equation form as

$$L_A = \left(\frac{V_D}{V_A}\right)^{12} \cdot L_D \qquad (1)$$

where L_A = lamp life when operated at voltage V_A

L_D = lamp life at design voltage V_D

The above equation can be rearranged to give

$$L_D = \left(\frac{V_A}{V_D}\right)^{12} \cdot L_A \qquad (2)$$

Normal design life L_D can be calculated from equation (2) if lamp life at voltage V_A is known.

Power dissipated by the lamp is equal to V^2/R where V is the voltage across the lamp and R is the filament resistance. Placing a limit on the maximum allowable lamp power dissipation (exceeding this limit for a specified time should cause the lamp to burn out) is therefore equivalent to placing a limit on the maximum voltage that can appear across the lamp. The voltage can be represented by V_A and the specified time by L_A of equation (2). As seen from the equation, the lower the limiting value of V_A (or the lower the maximum allowable power dissipation), the shorter will be the lamp life, L_D, under normal or design operating conditions.

improper bulb replacement cited earlier. Lamps designed to meet a 5 to 5 1/2 watt limit, however, will operate at their normal dissipation for at least 2000 hours - sufficient to last the life of the light string [11].

The electric shock hazard from overheated miniature Christmas tree light strings could be eliminated by requiring insulating material with a higher melting temperature to be used for lampholders. A maximum wattage/time specification imposed to reduce fire hazard will also, of course, reduce the electric shock hazard. However, the surface temperature of even normally operating lamps can be sufficiently high to cause the melting of some insulating materials. Unless lamp filament placement is more rigidly controlled or lamp envelope size increased, some additional requirement should be imposed to prevent melting and exposure of electrically live parts.

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(11) Lamp life can be computed via the equations presented in note 10. For lamps operated at more than $\pm$ 10% of rated design voltage, these equations may give values which vary widely from the actual results. Our concern is with lamps whose operating voltage V_A is much greater than their design voltage. Under these conditions, equation (1) may give values for L_A which are larger than is actually the case. The reason for this is that operation at higher than normal voltage causes higher than normal lamp surface temperatures. At surface temperatures above 100°C, the glass used to manufacture most lamp envelopes begins to outgas. Water vapor caused by the outgassing is disassociated by the hot filament into hydrogen and oxygen. The oxygen reacts with the hot tungsten to form tungsten oxide and thereby reduces filament life, L_A, from that predicted by equation (1). This equation can therefore be assumed to calculate <u>maximum</u> lamp life at the elevated voltage V_A. By this same reasoning, if lamp life at voltage V_A is actually measured, then equation (2) should give <u>minimum</u> expected lamp life at normal operating voltages.

Measurements on 12 volt lamps which are dissipating 5.5 watts indicate a voltage drop across the lamp of approximately 33 volts (V_A = 33 volts). If operating time at this wattage is 60 seconds (L_A = 60 sec), then the minimum operating time (L_D) at the normal design voltage (V_D = 12 volts) can be calculated from equation (2) to be 3117 hours. Four weeks of light string operation per year at 10 hours per day results in 280 hours of operation per year. At this rate, the lamp would last for 11 Christmas seasons under normal operating conditions.

The requirement can be either design or performance oriented. Performance oriented requirements are preferred, where possible, because they provide a manufacturer with greater freedom of approach to the problem. On occasion, however, design restrictive requirements may be necessary because of the unpredictability of the events which may befall the product to be regulated. This unpredictability of circumstances precludes specification of a performance test or tests for all situations. Miniature Christmas tree lights fall into this category.

The best approach for miniature Christmas tree light strings might be to incorporate both a performance test and a minimum design requirement. A performance criterion could be applied to fail lamps if there is melting sufficient to expose electrically live parts when a lamp which is dissipating maximum power rests against another lampholder from the same string. The design requirement could specify that lampholder material not melt to expose electrically live parts when subjected to some specified ambient temperature. The performance test would provide protection in the more common hazardous situations, whereas the design requirement would specify a minimum level of safety for situations that are not easily predictable. For instance, it is difficult to predict the worst situation that can result from incorrect lamp replacement because new lamps and new light strings are marketed each year. It is also difficult to predict the various acts that a consumer might perform in decorating with a light string that can cause high temperatures to build up around the lampholders.

AFTERWORD

The foregoing recommended hazard intervention mechanisms, developed in the course of these investigations, have been included in a Proposed Mandatory Safety Standard for Miniature Christmas Tree Lights and Similar Miniature Decorative Lights published by the CPSC in the Federal Register of May 3, 1978. Since that time, Underwriters' Laboratories, Inc., has proposed a revision to its voluntary Standard for Safety UL588 on Electric Christmas Tree and Decorative Lighting Outfits, effective October 1, 1979, which includes all requirements suggested by NBS and CPSC for the mandatory standard.

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1/ Modern Plastics Encyclopedia 1976-1977 (McGraw-Hill Inc., New York, NY) p. 471.

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3/ Smith, L., and Harwood, B., Incidents Related to Miniature Christmas Tree Lights - Christmas Season 1977, Consumer Product Safety Commission (U.S.), Special Report (Aug. 1978). 9p

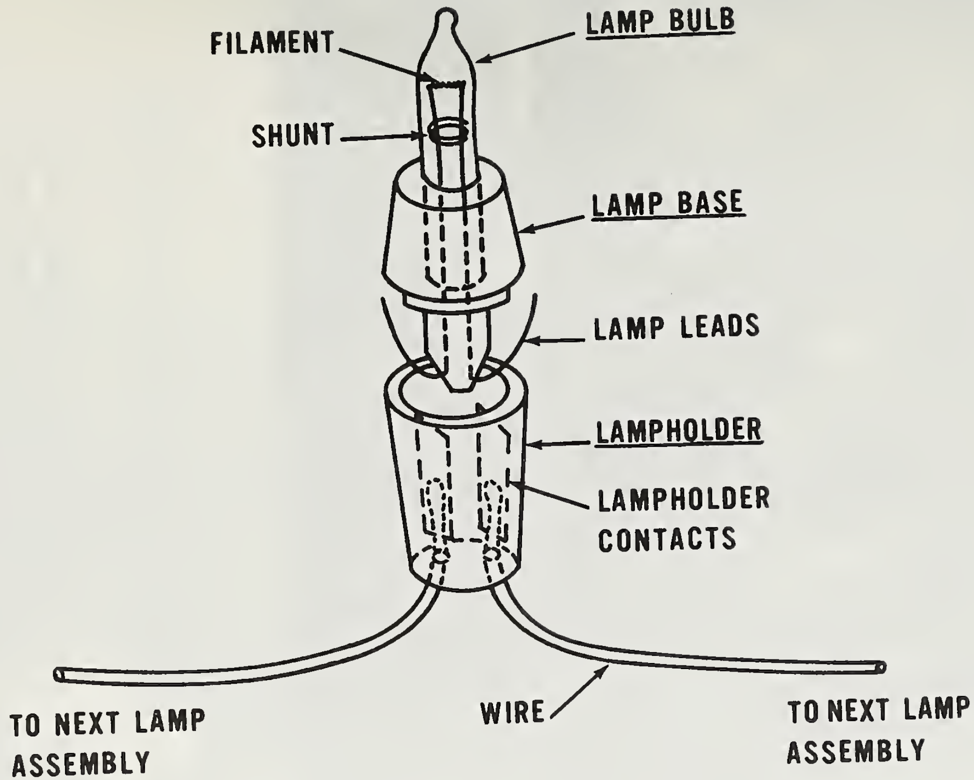


Figure 1. Illustration of a Lamp Assembly

The assembly is composed of three separable parts - lamp bulb, lamp base and lampholder.

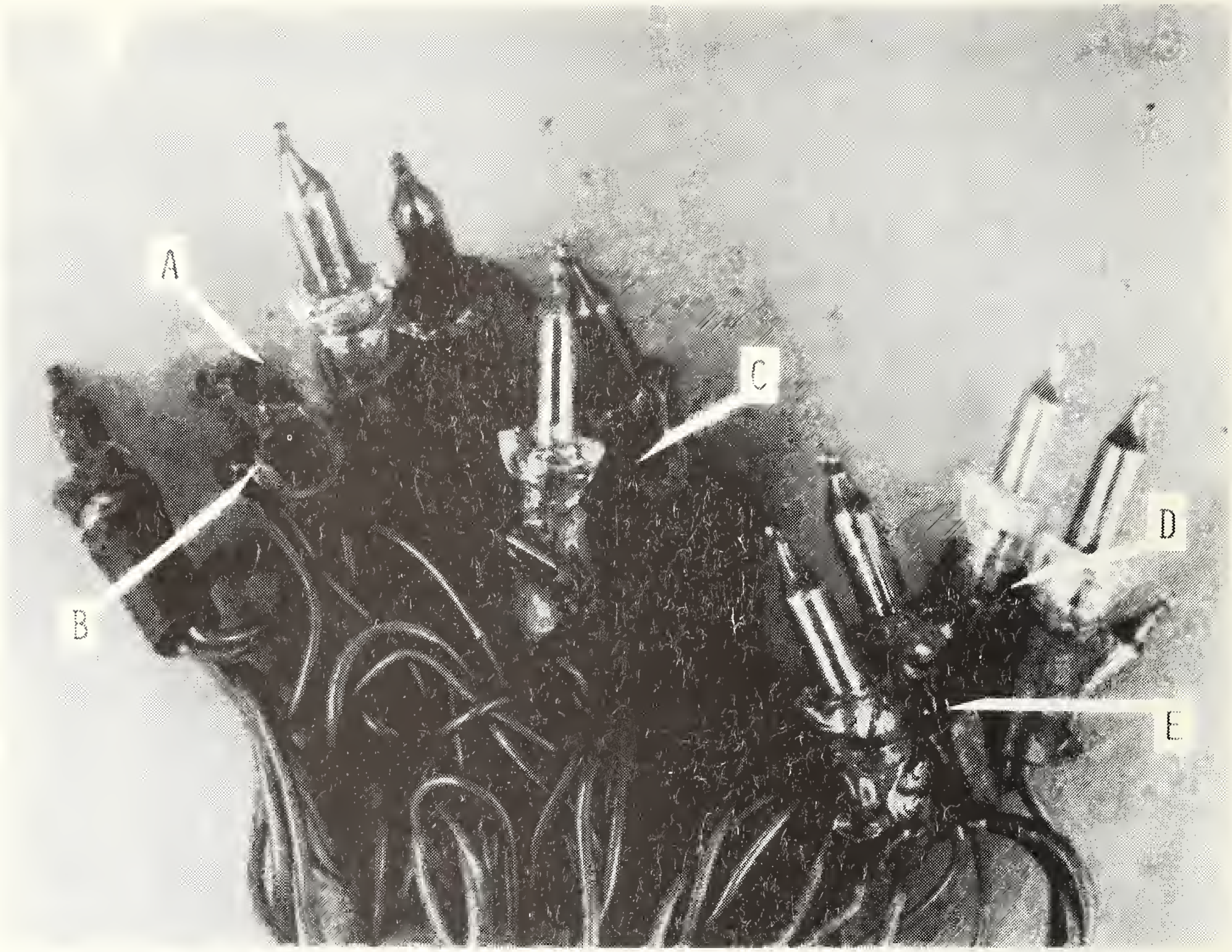


Figure 2. Melted Lampholders and Exposed Conducting Parts (A, B, C, D and E).

Exposure was caused by contact between hot normally operating miniature Christmas tree lamps and low melting temperature plastic lampholder material. The situation was aggravated by lack of adequate air flow around contact area.

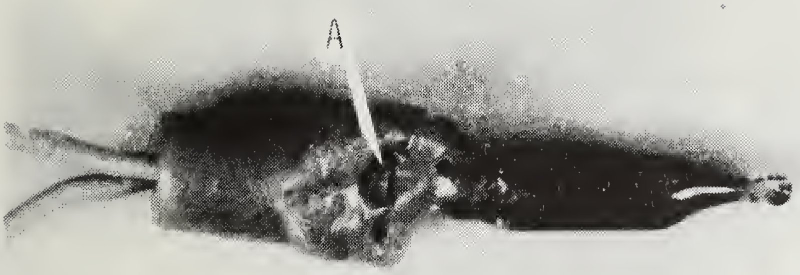


Figure 3. Melted Lampholder and Exposed Conducting Part (A).

Exposure resulted from heat trapped by a close-fitting decorative attachment that was placed over the lamp assembly. The lampholder is constructed from lower melting temperature plastic.

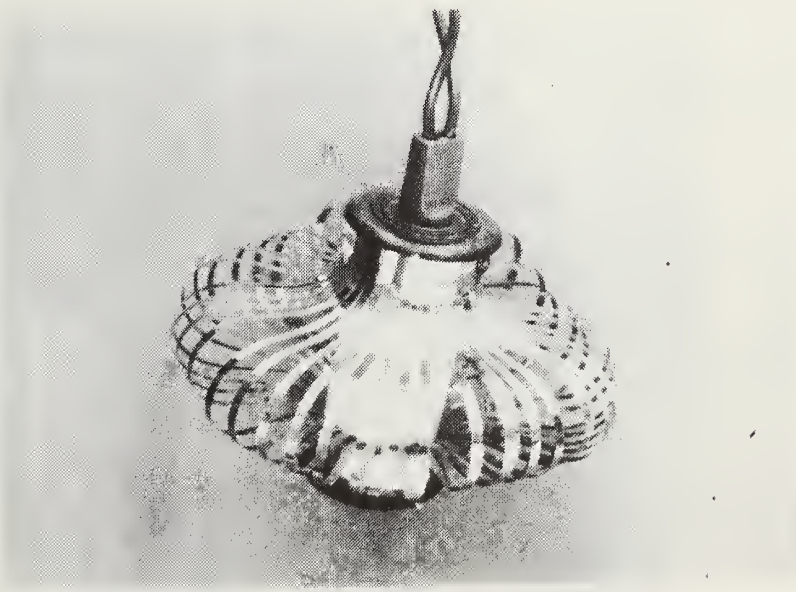


Figure 4. Decorative Attachment Used in Lamp Assembly Heating Tests.

A lamp assembly is shown partially inserted into the attachment.

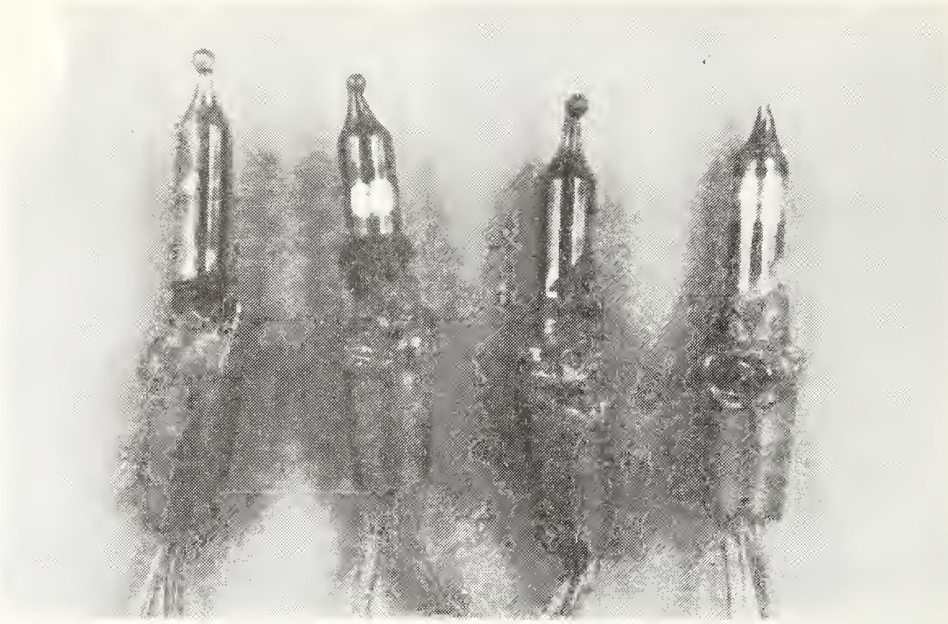


Figure 5. Lampholders Constructed from Lower Melting Temperature Plastic After Exposure to Heat Trapped by a Close-Fitting Decorative Attachment.

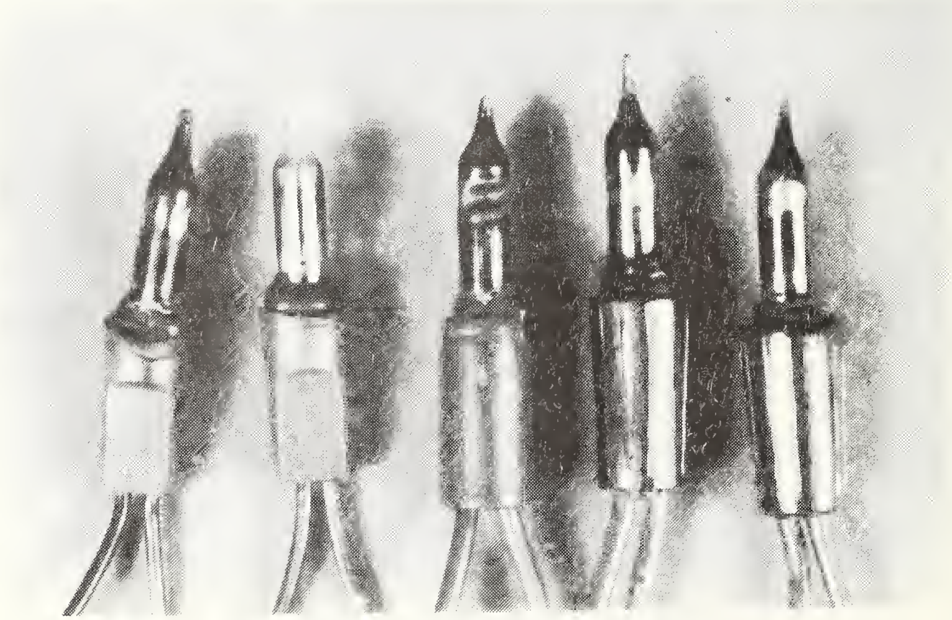


Figure 6. Lampholders Constructed from Higher Melting Temperature Plastic After Exposure to Heat Trapped by a Close-Fitting Decorative Attachment.

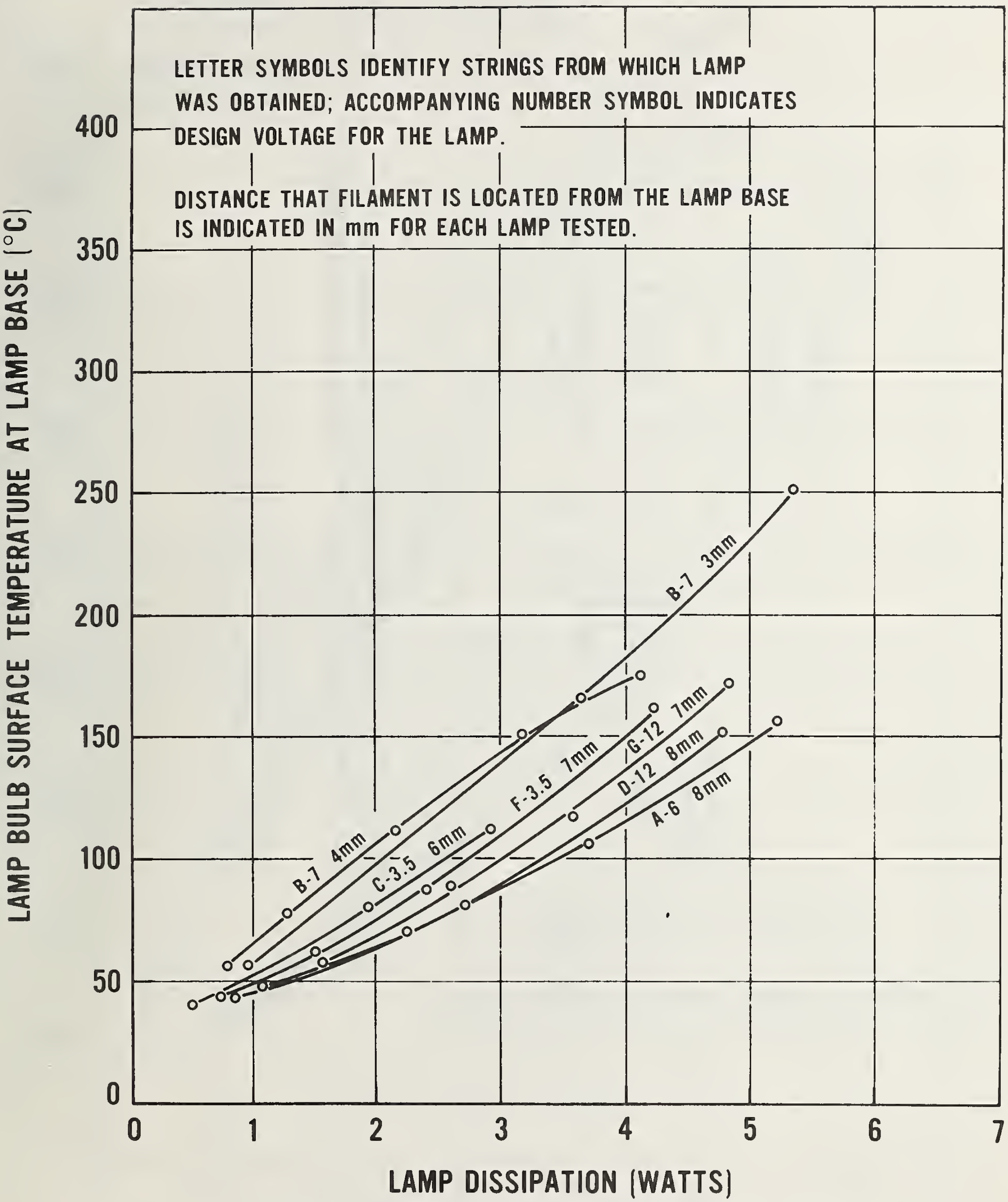
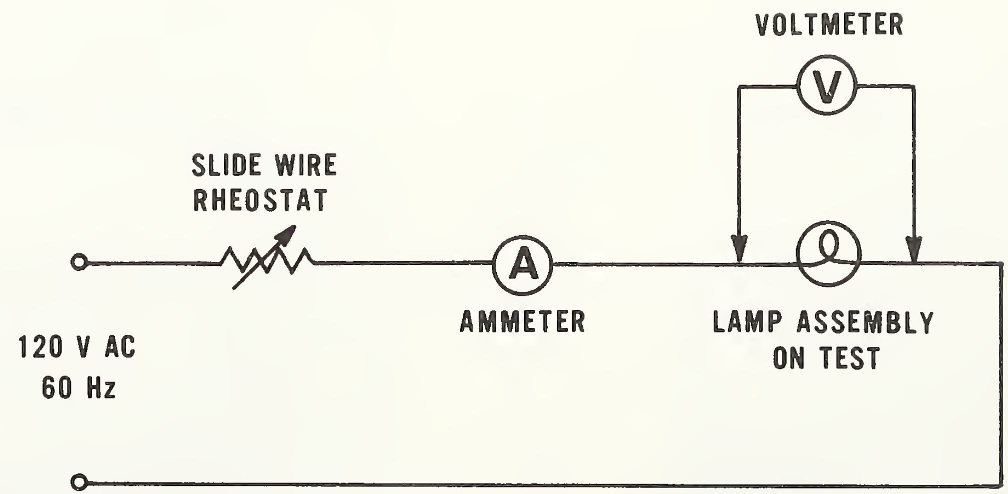


Figure 7. Bulb Surface Temperature Next to Lamp Base as a Function of Lamp Dissipation and Filament Location.



SLIDE WIRE RHEOSTAT SIMULATES REMAINDER OF SERIES-CONNECTED LIGHT STRING. LAMP WATTAGE IS PRODUCT OF VOLTAGE (V) AND CURRENT (A).

Figure 8. Schematic Diagram of Test Circuit for Individual Lamp Assemblies.

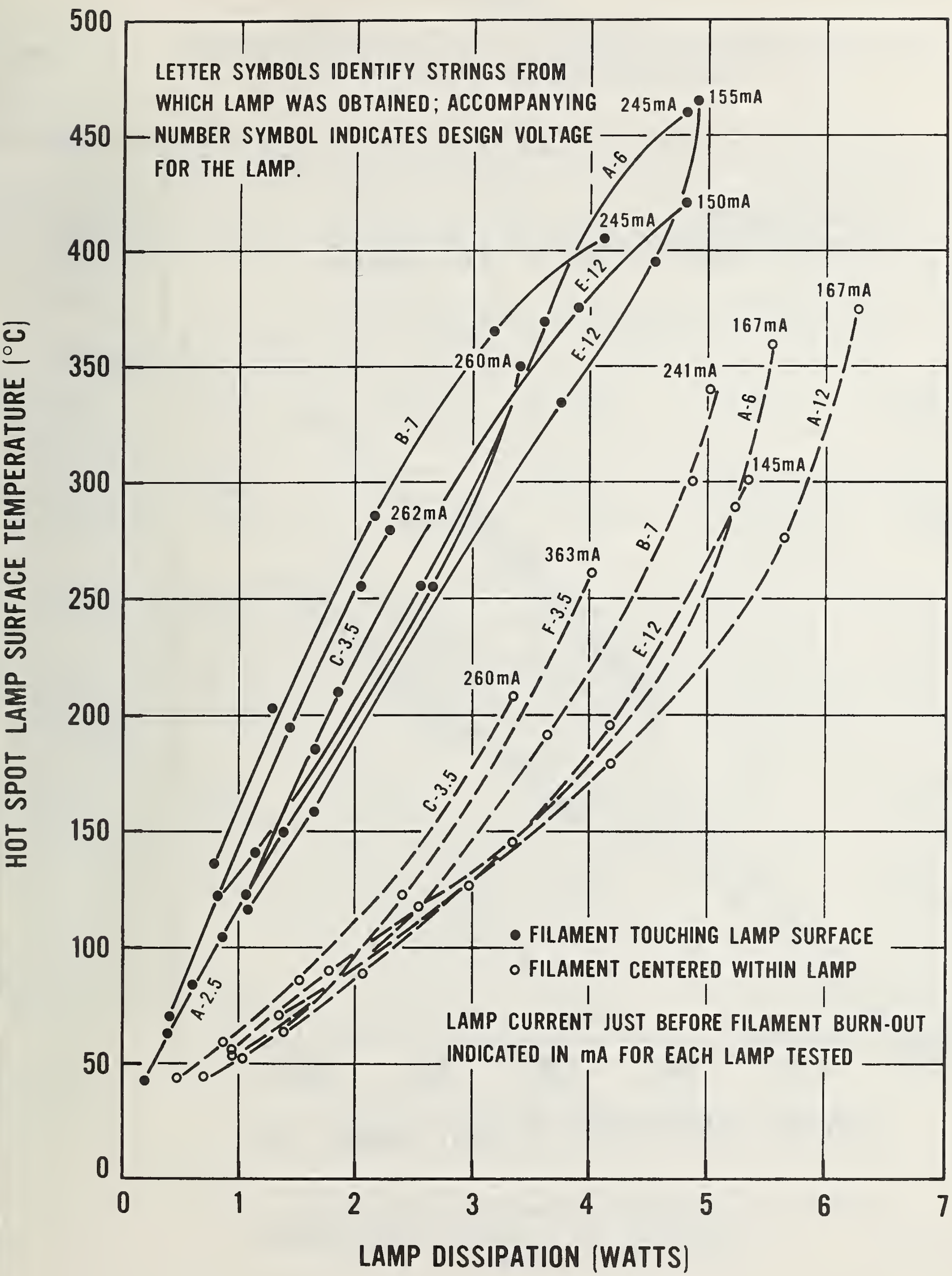


Figure 9. Hot Spot Lamp Surface Temperature as a Function of Lamp Dissipation and Filament Placement.

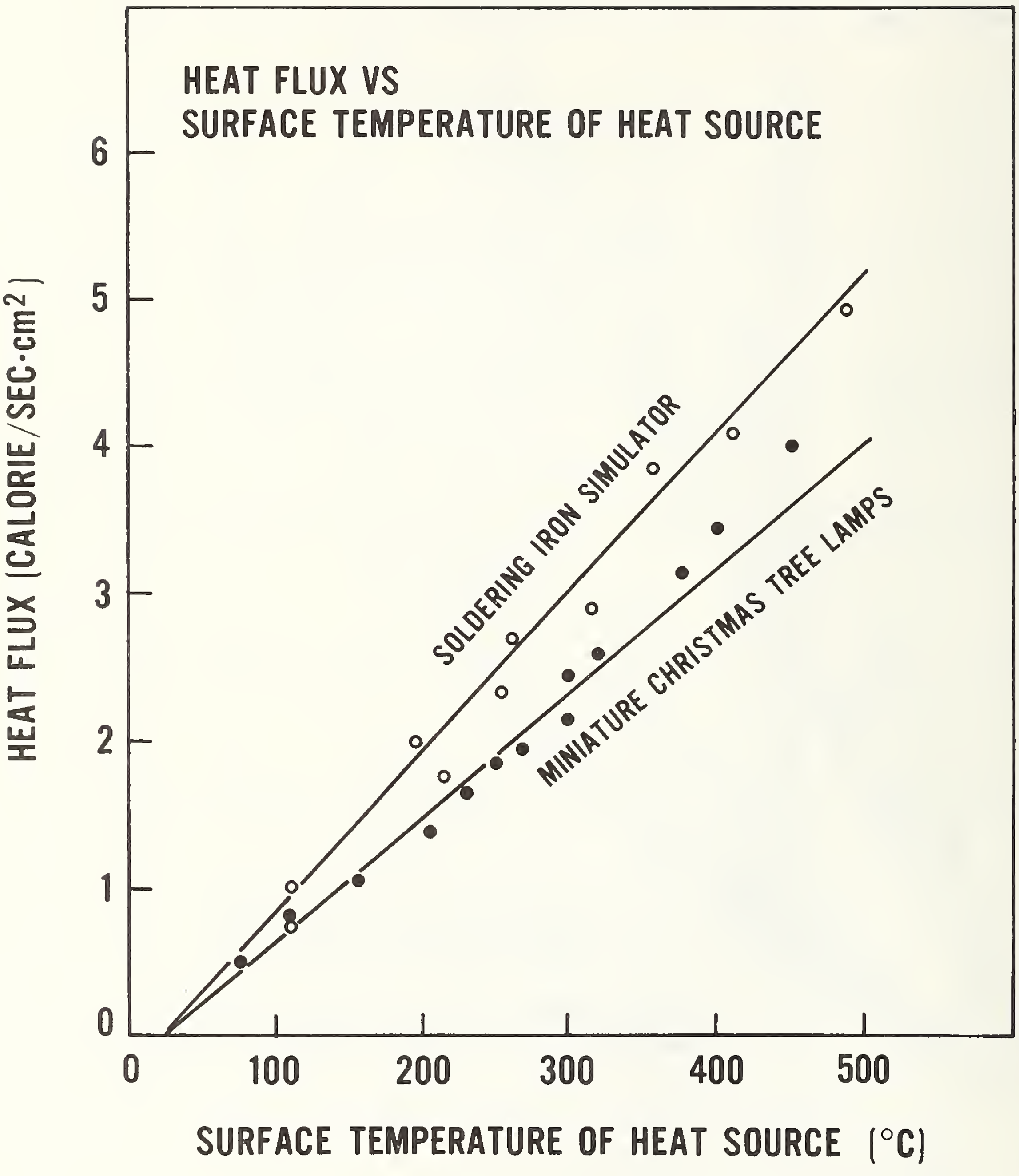


Figure 10. Comparison of Heat Flux Produced by Soldering Iron Simulator and Miniature Christmas Tree Lamps

TABLE 1

Ignition Test Results for Various Materials Obtained with a Simulated Miniature Lamp Heat Source

Simulation achieved by means of a borosilicate glass enclosed soldering iron.

Type of ignition and time to ignition are listed in the table. If significantly different results were obtained for a material/temperature combination, all results are listed with the corresponding percentage of attempts to which each applies shown in parenthesis.

Material	Hot Spot Temperature on Surface of Glass in °C				
	390-420	440-460	470-490	500-520	530-550
Absorbent cotton (untreated)	Glow 45-90 sec	Flame 30-45 sec	Flame 10-15 sec	Flame 6-10 sec	Flame 1-3 sec
Cotton dress on decorative attachment	Glow 45-90 sec	Glow 7-20 sec	Glow 4-10 sec	Glow (100%) 2-6 sec Flame (30%) 6-15 sec	Flame 1-5 sec
Tissue paper	Glow 75-120 sec	Glow 15-30 sec	Flame 10-20 sec	Flame 5-10 sec	Flame 1-3 sec
Christmas wrapping paper (non-foil type)	No ignition after 2 minutes	No ignition after 2 minutes	No ignition after 2 minutes	Flame (50%) 5-15 sec No ignition (50%)	Flame 1-6 sec
Newspaper	Glow 30-120 sec	Glow 10-20 sec	Glow 5-10 sec	Glow 3-8 sec	Flame 1-5 sec
Cheesecloth	Glow 90-180 sec	Glow (100%) 20-40 sec Flame (25%) 30-60 sec	Flame 15-25 sec	Flame 5-10 sec	Flame 2-5 sec
Cardboard (0.5 mm thick)	Glow 30-60 sec	Glow 15-30 sec	Glow 10-20 sec	Glow (100%) 5-10 sec Flame (75%) 40-60 sec	Glow (100%) 3-8 sec Flame (80%) 10-15 sec

TABLE 2

Data on Glowing Ignitions Caused by Actual Miniature Christmas Tree Lamp as Heat Source

Material ignited: cotton dress on a doll shaped decorative attachment

		#1	#2	#3	#4	#5	#6	#7
Lamp Type[1]		H-12	H-12	E-12	E-12	H-12	E-12	E-12
Lamp Color		red	blue	yellow	yellow	green	yellow	green
Filament Location		center	center	midway between center and edge	center	center	center	center
Conditions just Prior to Ignition	Lamp Current	175 mA	170 mA	164 mA	178 mA	164 mA	168 mA	168 mA
	Lamp Voltage	35 Vac	36 Vac	38 Vac	37 Vac	37 Vac	39 Vac	39 Vac
	Lamp Power	6.11 W	6.11 W	6.23 W	6.58 W	6.07 W	6.55 W	6.55 W
Time Lamp at High Power Before Ignition Attempt		20 sec	35 sec	115 sec	60 sec	20 sec	10 sec	15 sec
Time to Ignition After First Contact		50 sec	40 sec	15 sec	75 sec	90 sec	80 sec	90 sec
Surface Temp. of Lamp as Determined from Fig. 9[2]		425-450°C	425-450°C	425-450°C	450-475°C	425-450°C	450-475°C	450-475°C

[1]Letter symbols identify strings from which lamp was obtained; accompanying number symbol indicates design voltage for the lamp.

[2]Obtained by using "Lamp Power just prior to ignition" and the "Filament Location" information listed above for each lamp.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Failure to replace burned out lamps in series-constructed miniature Christmas light strings, or replacement with lamps of incorrect voltage rating, can lead to very high power dissipation by some or all of the lamps in the series string. Hot spot surface temperatures as high as 470°C were measured for lamps subjected to simulation of the above conditions. Additional testing showed that contact with surface temperatures above 390°C can cause glowing ignition, within two minutes, of cellulose material (e.g., tissue paper, decorative cotton) often found in the vicinity of Christmas light strings, and can cause flaming ignition in some samples of absorbent, untreated cotton. Furthermore, the hot spot surface temperature of normally operating lamps (no excessive power dissipation) can, particularly if the filament is off center, be higher than the melting temperature of some commonly used plastic insulating materials such as polyethylene. Contact between a hot lamp and insulating material can thus cause a shock hazard due to exposure of current carrying parts. Light string design and performance requirements that would prevent these hazards are discussed in the report.

This report is based on work funded by the Consumer Product Safety Commission as part of its program for development of a mandatory standard for miniature light sets.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Electric shock; fire; flaming ignition; glowing ignition; hazard; ignition temperature; lamp surface temperature; melting temperature; miniature Christmas lights; plastic insulating material; polyethylene; series-constructed

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