NIST Technical Note 1872

Investigation of Surrogate Smoldering Ignition Sources for Testing Soft Furnishings

Richard G. Gann
Morgan C. Bruns
Amanda P. Robbins
Edward J. Hnetkovsky
Michael H. Ladas

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.1872

National Institute of Standards and Technology
U.S. Department of Commerce

NIST Technical Note 1872

Investigation of Surrogate Smoldering Ignition Sources for Testing Soft Furnishings

Richard G. Gann
Morgan C. Bruns
Edward J. Hnetkovsky
Michael H. Ladas
Fire Research Division
Engineering Laboratory
Gaithersburg, Maryland, USA

Amanda P. Robbins
BRANZ Ltd
Porirua, 5240, New Zealand
(Current affiliation:
Sereca Consulting, Inc.
Calgary, Alberta, Canada)

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.1872

March, 2015

U.S. Department of Commerce
Penny Pritzker, Secretary

National Institute of Standards and Technology
Willie May, Acting Under Secretary of Commerce for Standards and Technology and Acting Director

DISCLAIMERS

The research on reduced ignition propensity cigarettes conducted by NIST since 1984 was done in the interest of saving lives and protecting property from cigarette-induced fires. In no way does it lessen or negate the health hazards and addictive nature of smoking as determined by the Surgeon General or suggest that NIST and the Department of Commerce condone smoking.

Certain commercial equipment, instruments, or materials are identified in this report in order to specify an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

Metric units are used throughout this document, except where standards are discussed that explicitly use non-metric units or where a commercial product is described in non-metric units.

This work was funded by the U.S. Consumer Product Safety Commission. The content of this publication has not been reviewed or approved by the Commission and does not necessarily reflect the views of the Commission; similarly, mention of trade names, commercial products, or organizations does not imply endorsement by the Commission.

National Institute of Standards and Technology Technical Note 1872
Natl. Inst. Stand. Technol. Tech. Note 1872, 100 pages (March 2015)

This publication is available free of charge from:
https://doi.org/10.6028/NIST.TN.1872

ABSTRACT

The introduction of cigarette ignition propensity standards has led to a reduction in the availability of high ignition propensity commercial cigarettes. Since high ignition propensity cigarettes are needed for soft furnishing flammability tests, a standard reference cigarette, SRM 1196, was developed. The current supply of SRM 1196 cigarettes is limited, and so the feasibility of a surrogate ignition source was examined. The surrogate ignition source should be repeatable, sustainable, relatively inexpensive, and should have a similar ignition propensity to the SRM 1196 cigarette on a broad range of substrates. A literature review identified several potential surrogate ignition sources including cartridge heaters, hot slugs, and materials that can smolder, such as charcoal, cotton plugs, and cotton rope.

Experiments quantified the heat transfer characteristics and ignition propensity of the SRM 1196 cigarette as a baseline for evaluating candidate ignition sources. In particular, thermocouples were used to measure the temperatures at the interface of the cigarette and the substrate for both reactive and inert substrates.

Screening experiments were performed to estimate the ignition propensities of the candidate surrogate sources. Analysis of and experiments with these sources found that cartridge heaters are impractical for routine testing and that commercial versions of the combustible materials do not show appropriate or repeatable values of ignition propensity. The use of hot slugs would require additional testing in which the materials, dimensions, shape, and mass were all systematically varied. Extensive testing to identify fabrics which, when supported on a foam slab, would lead to some, but not 100 % ignitions did not find enough fabrics to demonstrate equivalence to the SRM 1196 cigarette. Because of the unlikelihood of success, it is recommended that these tests not be performed and that the National Institute of Standards and Technology (NIST) order another supply of SRM 1196 cigarettes.

Keywords: cigarette; cigarette ignition propensity; fire; fire safety; fire tests; mattresses; smoldering

This page intentionally left blank.

TABLE OF CONTENTS

LIST OF FIGURES

This page intentionally left blank.

LIST OF TABLES

This page intentionally left blank.

1 INTRODUCTION

Cigarette ignition of soft furnishings (upholstered furniture and beds) has long been recognized as a leading cause of fires and fire fatalities [1]. To reduce the likelihood of these fires, the fire safety community has developed standards and implemented regulations that have resulted in modifying both the ignition source and the potential combustibles.

Several standards and regulations have been introduced to reduce the ignition susceptibility of soft furnishings. 16 CFR part 1632 is a Federal requirement for the cigarette ignition resistance of mattresses [2]. California TB 116 [3] and TB 117 [4], NFPA 260 [5] and NFPA 261 [6], ASTM 1352 [7] and ASTM 1353 [8], and the Upholstered Furniture Action Council (UFAC) test method [9] all address the cigarette ignition resistance of upholstered furniture and furniture components. The ignition source in all these tests has been a commercial test cigarette (CTC), an 85 mm (later 83 mm), unfiltered Pall Mall that had been identified as a very strong igniter [10].

Research beginning in the 1980s [11,12] led to a standard for measuring the ignition propensity of cigarettes [13]. Regulations citing this standard now mandate less fire-prone cigarettes for all cigarettes sold in the United States and Canada. Such cigarettes are labeled FSC, for fires standard compliant. The premise for mandating FSC cigarettes is that soft furnishings would continue to be tested using a high ignition potential cigarette, while the cigarettes being smoked and occasionally dropped onto soft furnishings, would be of reduced ignition propensity. The difference between these wo types of cigarettes would result in a decrease in casualties from cigarette-initiated fires.

However, a consequence of these regulations was that the classic version of the CTC was no longer commercially available.

In response, the National Institute of Standards and Technology (NIST), with shared support from the Consumer Product Safety Commission (CPSC) developed a standardized cigarette, SRM 1196 (Figure 1), to replace the now defunct commercial test cigarette. The SRM 1196 cigarette is (83 ± 2) mm long, has a mass of (1.1 ± 0.1) g, has a tobacco packing density of (0.270 ± 0.20) g/cm^3 and an ignition strength of (90.1 ± 2.1) percent full-length burns (PFLB), as measured using ASTM E 2187, as modified in Reference 14.

First available in 2006, the supply of SRM 1196 cigarettes was sized to last approximately 15 years. Prior to exhausting this initial supply, a new batch of cigarettes would be procured and certified.

However, CPSC and NIST were not fully confident that there would be a manufacturer willing and able to produce cigarettes with the ignition propensity of SRM 1196 in perpetuity. Thus, it was decided to explore the potential for a surrogate smoldering ignition source (SIS) to replace the SRM 1196 cigarette. A viable surrogate would have an ignition propensity that is precise, repeatable, and similar to that of the SRM 1196 cigarette. The surrogate source should be reusable or made of sufficiently specified, consistently replaceable materials. This report presents the results of a research project aimed at identifying and characterizing such a surrogate.

Figure 1. SRM 1196.

The organization of this report is as follows. Following a description of the phenomenology of smoldering ignition (Section 2), there is a summary of a review of the published literature (Section 3). In this review, we identified sources and substrates that had been used in a wide range of experiments, taking note of the data that characterized the ignition process and making observations of the utility of the types of ignition sources.

This information led to the formulation of a list of attributes of a desirable surrogate for the SRM 1196 cigarette (Section 4). Section 5 describes baseline thermal data for the reference cigarette on an inert substrate and on substrates capable of igniting. This required the development of apparatus for conducting the experiments. Section 6 presents a list of types of potential surrogate sources and the results of testing representatives of these types. It was becoming clear that a single SIS might not be appropriate for testing on both flat surfaces and in crevices. Thus, by agreement of CPSC and NIST staff, the research then focused on an SIS for the flat surfaces characteristic of mattress testing under 16 CFR part 1632, rather than the geometrically more complex surface junctures onto which a cigarette might drop on upholstered furniture. Section 7 describes the initiation of research to home in on specific design and operating parameters for an SIS. Section 7 also contains interpretation of the findings, leading to a conclusion that stationary, pre-heated "slugs" were the most promising candidates for replicating the ignition performance of SRM 1196 cigarettes. However, extensive screening of commercial fabrics indicated that finding materials for a rigorous comparison with the cigarette was difficult and an estimate of the process required to identify an equivalent ignition source for the test configurations in 16 CFR 1632 was not assured of success. Section 8 concludes this Technical Note with a recommendation that an additional supply of SRM 1196 cigarettes be procured and certified.

2 IGNITION TO SMOLDERING COMBUSTION

Smoldering ignition can be initiated when a burning cigarette comes into contact with an item of soft furnishings, such as a sofa or a mattress. A generic smoldering ignition scenario is sketched in Figure 2. The burning cigarette has a hot region known as the coal in which smoldering combustion takes place. This coal moves down the cigarette in the direction of the unburned tobacco column. Some of the heat from the coal goes toward heating the substrate. As a susceptible substrate increases in temperature, it begins to pyrolyze, creating a porous, carbonaceous material that is susceptible to smoldering combustion. Oxygen from the air percolates through the pores of the substrate to the charred material, reacting at the solid surfaces. Since smoldering is exothermic, both the cigarette and the substrate are heated by the release of this chemical energy. This reaction process is slow, and the heat release rate is very small and sensitive to heat losses to the surroundings. However, if the substrate smoldering front advances deep enough into the substrate, then the reaction zone becomes sufficiently insulated that the smoldering reaction is self-sustained. That is, the substrate will continue smoldering even after the cigarette goes out or is removed. The likelihood of self-sustained smoldering depends on many factors, including the cigarette, the upholstery fabric, the padding materials, and the geometry of the cigarette on the substrate. For a specific cigarette, it is only the characteristics of the substrate and the cigarette-substrate contact that determine the likelihood of self-sustained smoldering.

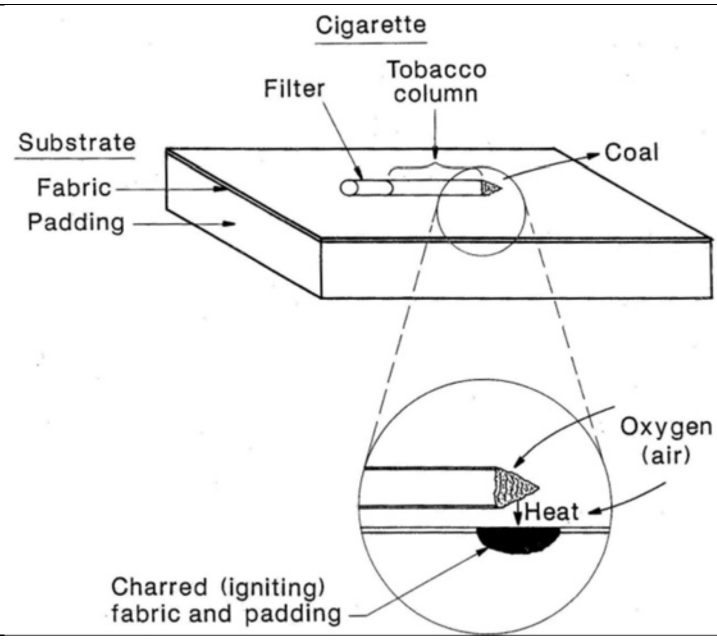


Figure 2. Diagram of Cigarette-initiated Ignition of Soft-furnishing Materials [15].

Over several decades of research into cigarette ignition of soft furnishing, some general findings have emerged that promote the onset of substrate smoldering.

- Upholstery fabrics and mattress ticking that are 100 % cellulosic (which generally means 100 % cotton), or fabrics with a high cellulosic content. These fabrics can themselves smolder, providing heat to the padding materials after the cigarette has extinguished. By contrast, thermoplastic fibers tend to melt, an endothermic process that absorbs some of the smolder-generated heat. The molten plastic has no internal surfaces at which the oxygen can react. Leather, vinyl, wool, and silk themselves do not smolder.

- Padding materials that maintain a porous structure when heated by a cigarette or a smoldering upholstery fabric. Cotton batting and conventional flexible polyurethane foams behave in this manner. Thermoplastic filler materials are not susceptible to smolder for the reasons described in the preceding paragraph.
- Cigarettes that burn longer and more strongly and that have better thermal contact with the substrate.

3 LITERATURE REVIEW

Many smoldering studies have utilized various ignition sources to initiate smoldering combustion. A review of these studies is provided in NIST TN 1710 [16]. The following is an abbreviated summary of that report. This summary includes discussions of alternate ignition sources, the thermal characteristics of burning cigarettes, and the thermal response of substrates to burning cigarettes.

3.1 Potential Smoldering Ignition Sources

The most common (non-cigarette) type of source for achieving smoldering ignition in research has been the electrical resistance heater. Typically, these heaters take the form of cartridges [17], hot plates [18], or variously shaped wires [19]. From the literature, it is clear that resistance heaters can initiate smoldering on a variety of substrates, are able to assume a variety of geometric configurations, and are easily controllable in terms of power output. However, these sources differed from the cigarette in that they were more massive, and no one had experimented with the idea of moving the area of hot contact with the substrate.

While these heating elements were generally placed in direct contact with the fuel package so that the dominant mode of heat transfer was conduction, some researchers have used heaters to transfer heat to the surface of the fuel radiatively [20]. This approach overcomes the drawbacks of the resistance heaters, but smoke and pyrolysis products can significantly attenuate the incident radiation, making it difficult to control heat transfer to the substrate.

The electrical power leads for resistance heaters can be a nuisance, both in the research laboratory and in product testing. Consequently, there has been some use of non-electric igniters. One class of non-electric igniters consists of heated metallic solids, ranging from small nuts [21] to flat sheets [22]. Such materials can be heated on a hot plate or in a furnace and transported directly to the ignitable substrate. Typical temperatures range from approximately 250 °C to 900 °C. A key difference from the cigarette is that, since the source is not powered, the temperature at the substrate surface rapidly decreases. It is possible that the cooling could be mitigated by using materials with carefully selected thermal properties.

As an alternative, several chemically reacting igniters have been used to initiate smoldering combustion of substrates. The most common class of these igniters is that of combusting cellulosic materials. In addition to conventional test cigarettes, cotton [23], paper [24], cellulose powders [25], and incense sticks [26] have been considered as smolder igniters. Among non-cellulosic reacting igniters, synthetic polymers [27], intumescent composites [28], and methenamine pills [29] have been tested.

3.2 Thermal Characteristics of Burning Cigarettes

Many igniters have proven useful for studying smoldering, but for flammability tests it is necessary to use a source with similar thermal characteristics to those of a burning cigarette. In the literature, commercial cigarettes have been characterized in terms of several thermal parameters including the length of the glowing coal, the burning rate (i.e., the rate of movement of the coal), cigarette temperatures and temperature profile, heat output, and mass loss rate.

The length of the glowing coal has been measured to be in the range of 5 mm [15] up to 30 mm [30]. It has been observed that the length of the burning coal depends upon the distance it has moved along the tobacco column [30], the substrate [30] and the orientation of the cigarette with respect to the substrate [15]. It appears that more isolated orientations, such as free burning, result in shorter coal lengths.

Smolder velocities for typical cigarettes range from around 0.05 mm/s to 0.12 mm/s [15]. Less insulated substrate scenarios result in faster burn rates. It appears that mass burn rate increases linearly with time, and that coal length is proportional to burn rate for free burning cigarettes [31].

Cigarette temperatures have been measured at various locations using thermocouples (TCs) and infrared (IR) cameras. Thermocouple measurements are difficult because of the relatively low thermal inertia of the tobacco column with respect to that of the thermocouple bead and wire. Consequently, very thin wires must be used in order to avoid significant heat conduction up the length of the TC wire. Peak temperatures along the centerline of the tobacco column have been measured to be from 600 °C to 780 °C [32]. These peak temperatures depended on the cigarette, the substrate, and the location along the substrate. At the interface between a cigarette and a substrate consisting of a single piece of fabric covering polyurethane foam, Salig [30] measured peak TC temperatures ranging from 310 °C to 560 °C. These values depended on the fabric and the distance along the length of the cigarette. Gann et al. [15] measured peak TC temperatures between a cigarette and a calcium silicate board to be between 372 °C to 470 °C for several different cigarettes. Surface temperature measurements based on IR camera analysis ranged from 590 °C [33] to 680 °C [31].

Temperature measurements can be used to infer how much heat a cigarette is releasing. However, it is ultimately the heat flux that determines the ignition propensity of a cigarette. Cigarette heat fluxes have been measured using Schmidt-Boelter type heat flux gauges [15]. Average peak heat fluxes from a typical cigarette were found to range from 47 kW/m^2 for a typical crevice test to 71 kW/m^2 for a free-burning configuration. Another approach for measuring heat output is to use oxygen consumption calorimetry. The total heat output of a cigarette on a glass slide was measured to be 5.4 W, using oxygen consumption calorimetry [31].

The mass loss rate for a cigarette is proportional to heat release rate (assuming a relatively uniform effective heat of combustion of the tobacco) and is much easier to measure. Measured mass loss rates ranged from 38 mg/min to 55 mg/min on single layer of chromatography paper to 14 mg/min to 53 mg/min on a single layer of fabric atop flexible polyurethane foam [34]. One problem with such measurements is that the mass loss of the cigarette cannot be completely decoupled from that of the substrate.

3.3 Thermal Response of Substrates

If a surrogate smoldering ignition source is to be used on a range of substrates, it is important to understand the thermal response of substrates to cigarettes. Specifically, it is important to know the temperature distribution evolution below the cigarette.

Temperature measurements inside flexible polyurethane foam with a single layer of upholstery fabric were found to greatly depend upon the upholstery fabric [30]. For one (Doblin) fabric, temperatures fell off from an average of 510 °C at 25 mm below the surface to 430 °C at 50 mm below the surface. For a blue cotton duck fabric, the temperatures in the substrate ranged from an average of 85 °C at a depth of 25 mm to ambient temperatures at 50 mm.

Gann et al. [15] measured the surface temperatures of a one-cushion mock-up using an IR radiometer. These temperatures significantly varied with the cigarette. For a relatively high ignition propensity cigarette, temperatures within 2.5 mm of the cigarette were over 450 °C and fell off to less than 400 °C at distances of 5 mm and greater.

This page intentionally left blank.

4 CONSIDERATIONS FOR A SURROGATE IGNITION SOURCE

4.1 Types of Characteristics

The traits of a surrogate ignition source (SIS) fall into two categories. The first category involves the similarity of test behavior between the surrogate and the SRM 1196 cigarette. These facets are presented in Sections 4.2 and 4.3. The second category reflects the makeup of the device. These facets are presented in Sections 4.4 through 4.6.

4.2 Test Performance

A true surrogate for the SRM 1196 cigarette would match its ignition performance. The same fractions of the specimens of components or composites that ignited when tested with the cigarettes would ignite when tested with the surrogate.

In practice, truly *identical* test performance is not readily discernible, since only a small number of specimens of a particular material or composite are tested. Furthermore, it is not clear how much of a difference in the potency of the SIS would result in a difference in fire losses. For example, the advent of the less fire-prone cigarettes over the past several years has resulted in an approximately 30 % reduction in the number of deaths from cigarette-initiated fires [1]. This corresponds to a *large* reduction in the measured ignition strength of the cigarette. However, the relationship between a *moderate* change in the measured ignition strength of the cigarette on the susceptibility of beds and furniture, and thus on the number of cigarette-ignited fires, is not known. For example, the measured ignition strength of the CTC varied (at least) between 1992 and 2008 [14]. The bed fires in each of those years involved beds of different ages, i.e., beds that had been tested (when new) in different years with cigarettes of varying strength. Linking each bed fire to the ignition strength of its test cigarette is not possible.

The important practical metric for equivalence is that classes of fabrics, padding materials, and their composites not show large changes in test performance from past experience.

4.3 Preservation of Thermal Physics

The initiation of smoldering in the test substrate is a result of a certain amount of heat being applied over a certain area for a certain time interval. While it may not be essential that the temperature, area, and heating time for the surrogate precisely match the values for the cigarette, it would be unwise to accept a surrogate with wide deviations without establishing some degree of equivalence. This is especially important for testing on substrate materials that undergo a phase change while chemically decomposing, e.g., thermoplastics.

In establishing this equivalence, it is not necessary that a surrogate source be covered if the cigarette is required to be covered in the test method. It might also be unnecessary that the thermal profile be qualitatively similar, noting that in the studies found in NIST TN 1710, none of the alternate ignition sources had a hot spot that moved in the way that the cigarette coal moves.

4.4 Ease of Use

In the current tests for cigarette ignition resistance of furniture mockups and mattresses, an experienced test operator can light the test cigarette and place it on the test specimen with little or no perturbation of either the cigarette or the substrate. (However, there is the potential for some disturbance while placing the cover sheet over the lit cigarette.) It is important that a test operator be able to apply a SIS without significant disturbance. This is especially important in the case of mattress testing, where the test specimen is subjected to 18 cigarettes simultaneously. Furthermore, the multiple ignition sources should not interfere with each other.

4.5 Composition Uniformity

The SRM 1196 cigarettes are relatively uniform in their initial composition and, despite being made of organic components, are stable over time when properly stored. It should be possible, over time, to obtain units of the surrogate source with at least a similar degree of uniformity.

4.6 Cost

The cost of an SRM 1196 cigarette is currently about $0.70 and is but a small fraction of the total cost of performing a test. A surrogate should not prohibitively increase the cost of a test. However, a more expensive surrogate could be considered is if it is reusable without substantial maintenance between uses.

5 SRM 1196 PIERFORMANCE REFERENCE DATA

5.1 Types of Measurements

Surrogate ignition sources can be screened by comparison to the ignition source they are intended to replace—namely, the SRM 1196 cigarette. Two types of data are valuable in this comparison. In the first, the ignition source is placed on an inert substrate. This enables obtaining information on the time- and space-evolution of the heat generation/heat transfer process without the confounding effect of possible exothermic substrate chemistry leading to ignition. Furthermore, test data on an invariant, well defined substrate can become the basis for quality control of a surrogate source in manufacture and in practice. It would be relatively straightforward to compare the thermal data obtained using a surrogate source with the data from the SRM 1196 cigarette. The challenge lies in relating any differences in thermal data between the SRM 1196 cigarette and the surrogate to any difference in ignition potential.

The second type of data is obtained by placing the ignition source on a more realistic, reactive substrate, such as a sheet of fabric over a slab of an ignitable padding material. There is the potential for distinctly greater variability, since the ease of ignition is dependent on the choice of substrate component. Furthermore, the repeatability of the test results is dependent on such factors as variability of the component materials, the care with which the substrates are assembled, and the ability to place the SIS on the substrate consistently.

In this project, measurements of both types were made of the temperature field at the ignition source/substrate interface as a function of time. In addition, we obtained the length of the hot cigarette coal and the linear burn rate.

5.2 Apparatus

5.2.1 Inert Substrate

The inert substrate consisted of a brass plate with two layers of filter paper on top. This is the same substrate that was used to quantify the ignition strength of the SRM 1196 cigarette [14]. This substrate was chosen because it was already "tuned" to the ignition strengths of the CTC and the SRM 1196 cigarette and had been demonstrated capable of quantifying differences among CTC batches of different vintages and ignition strengths. The substrate consisted of a square brass plate, nominally 203 mm (8 in.) on a side, and 6.35 mm (0.25 in.) thick. On top of the plate were two pieces of Whatman No. 2 filter paper to disperse the water vapor generated by the cigarette combustion, preventing its pooling under the cigarette coal and extinguishing it. After each test, the brass plate was cleaned with ethanol, and the paper was replaced.

On top of this substrate was placed a ring with two pins that enabled repeatable location of the test cigarette. On top of this ring was placed a polymethylmethacrylate (PMMA) collar that supported six thermocouples (TCs) that ran parallel to a diameter of the collar, shown schematically in Figure 3 and photographically in Figure 4. The spacing between the TCs was 4 mm. The TC junctions were aligned along a radius of the collar. A cigarette was placed perpendicular to the wires, so that the cigarette coal passed over the junctions as it burned. In order, the coal first passed over TC6, then TC5, etc. The bead of TC1 was nominally 32 mm from the butt (unlit) end of the cigarette; TC2 nominally 36 mm, etc.

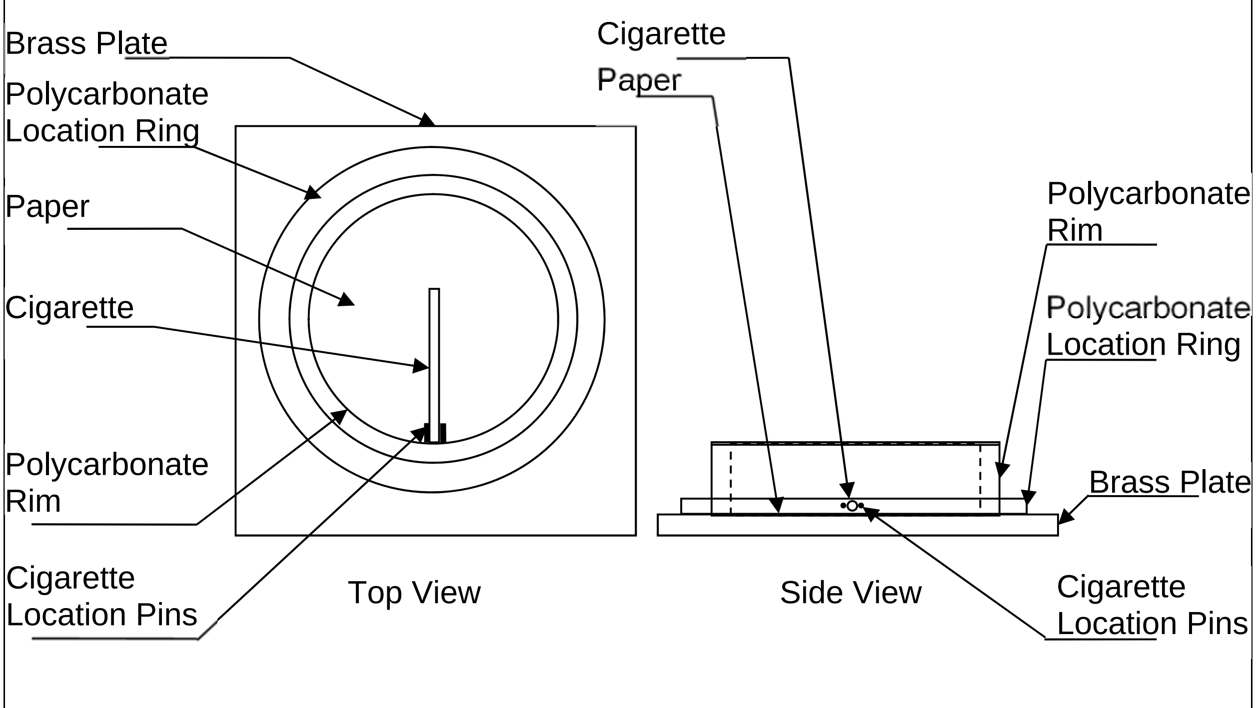


Figure 3. Diagram of the Inert Substrate.

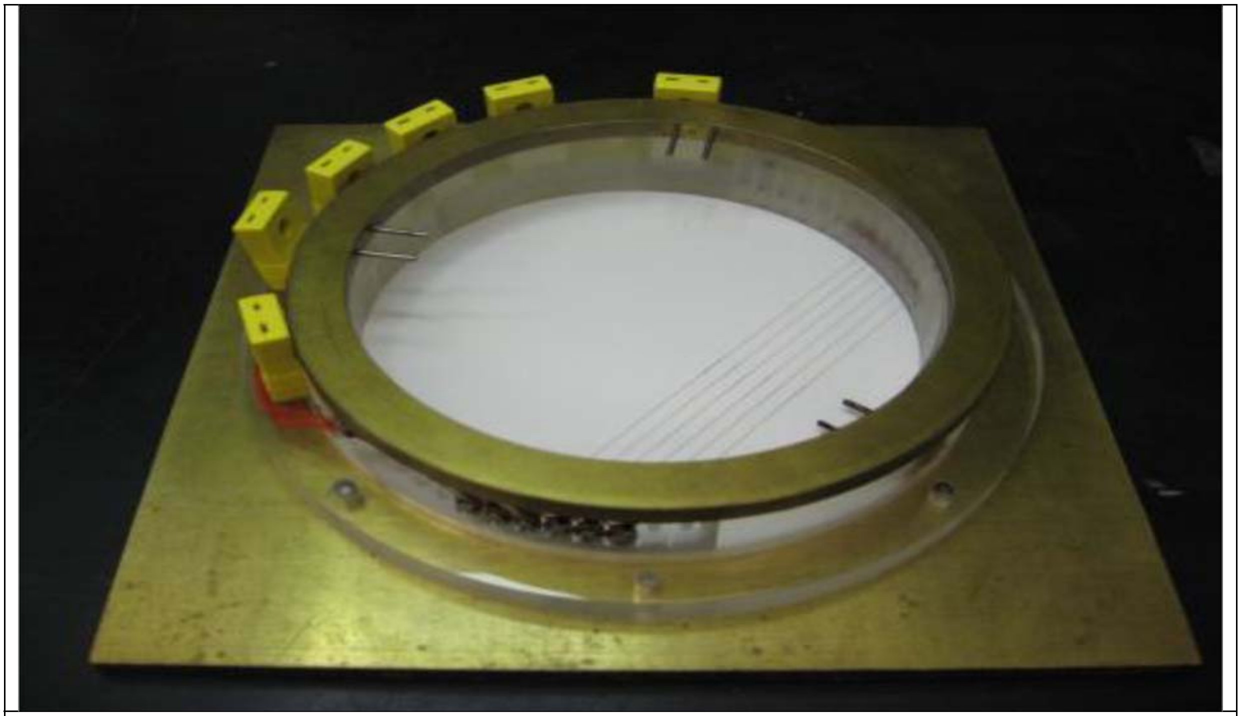


Figure 4. Thermocouple Array for Measuring Surface Temperatures on Top of the Inert Substrate.

A series of experiments was conducted to select the thermocouple bead diameter. The criteria were low influence of TC bead diameter on the recorded peak temperature and reasonable durability of the TC during use. The TCs examined were all unsheathed Type K (chromel-alumel) devices that were commercially available. The bead diameters investigated were 0.025 mm (0.001 in.), 0.050 mm (0.002 in.), 0.075 mm (0.003 in.), 0.125 mm (0.005 in.), and 0.25 mm (0.01 in.).

It was observed that a TC did not always lie flat after being strung on the collar. This was because of the method of manufacture of the bead - the two wires were spot welded, producing a local V-shape when the parent wires were separated. This geometry can only lie flat on the paper in two orientations when strung across the PMMA rim. Therefore, it was important to use care in orienting the TC during the stringing of the rim to ensure that each TC was as flat as possible against the surface of the substrate. This was especially time-consuming when testing in the crevice configuration. Thermocouples of smaller diameter wire and beads were less a problem than larger sizes.

However, the smallest TCs (i.e., those with the 0.025 mm and 0.050 mm beads) broke fairly often during adjustment of the location wires at their attachment points to the PMMA rim; i.e., before a test began. Therefore, they were removed from further consideration. TCs with larger (at least 0.075 mm) beads were found to survive installation and were more likely to remain unbroken after multiple tests.

As a result of these findings, attention focused on two TC sizes: 0.075 mm (0.003 in.) and 0.125 mm (0.005 in.).

An additional consideration was the potential deterioration of the TC performance with repeated use. Therefore, one set of 20 tests was performed where Tests 1 through 16 were performed sequentially without cleaning or replacement of the TCs. The last four tests of the set, Tests 17 through 20, were performed with the TCs cleaned between each test. This cleaning involved wiping each TC with ethanol applied by a small paint brush. To examine whether there was a significant effect of bead size, TC1 through TC4 had 0.75 mm beads; TC5 was of larger diameter, with a 0.125 mm bead. Thermocouple temperature measurements were recorded during the smoldering of SRM 1196 cigarettes on two layers of certified Whatman No. 2 filter paper (rough side up) on the inert substrate. In these tests, a prototype version of the PMMA collar was used. It supported five TCs. The distances of the five beads from the butt end of the cigarette were: TC1: 42 mm, TC2: 46 mm, TC3: 50 mm, TC4: 60 mm, and TC5: 68 mm.

Figure 5 shows the peak temperatures recorded during these experiments. Table 1 summarizes the observed temperatures and the variability in these measurements. The data from Test 1 were not used in the ensuing analysis because the cigarette distorted unusually and also TC4 broke.

The variability in the test-to-test peak temperatures for each TC is typical of all the cigarette tests on the inert substrate. While it might appear that the average peak temperatures in Tests 17 through 20 are slightly higher than those in the first 16 tests, the differences are within one standard deviation and are thus are not statistically significant.

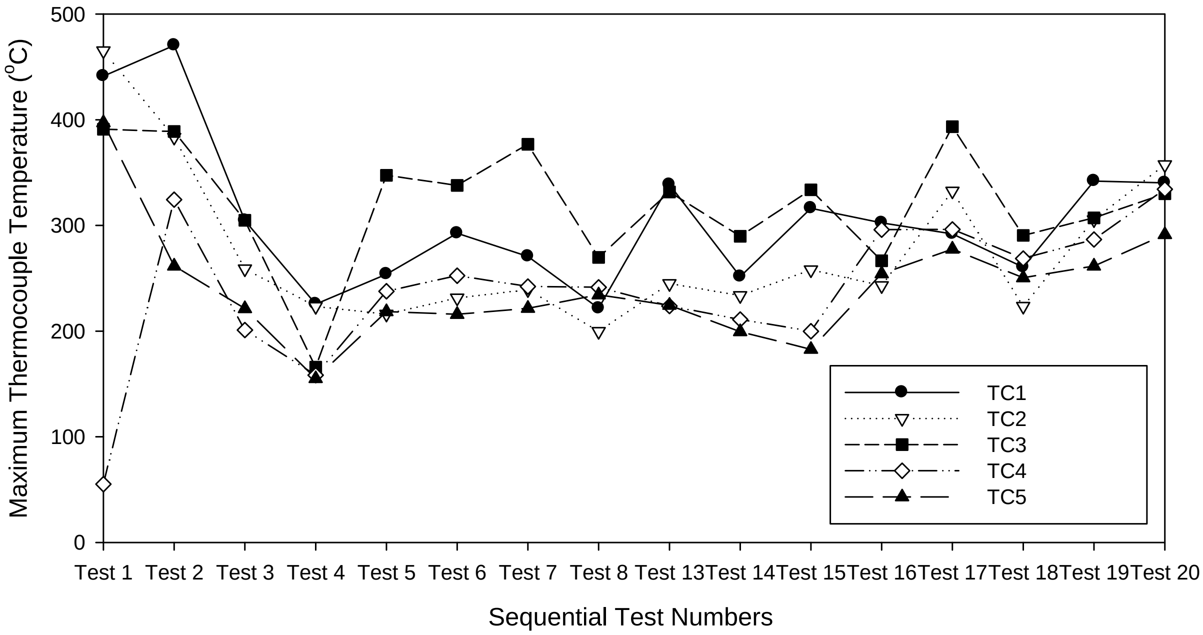


Figure 5. Uniformity of Peak Thermocouple Temperatures (Prototype Collar) for 20 Sequential Tests of Uncovered SRM 1196 Cigarettes on the Inert Substrate.

Table 1. Summary of the Peak Thermocouple Temperatures for the Test Results in Figure 5.

		Thermocouple Number				
Tests No.		**TC1**	**TC2**	**TC3**	**TC4**	**TC5**
2 to 20	Average Peak Thermocouple Temperature (ºC)	296	264	322	251	231
	Standard Deviation (ºC)	56	49	52	45	34
2 to 16	Average Peak Thermocouple Temperature (ºC)	292	254	320	238	220
	Standard Deviation (ºC)	60	42	55	41	30
17 to 20	Average Peak Thermocouple Temperature (ºC)	309	305	330	296	270
	Standard Deviation (ºC)	40	58	45	28	18

Similarly, the peak temperatures measured using the 0.125 mm diameter TC5 might appear to be lower than the peak temperatures measured using the finer TCs; however, these differences are not statistically significant. (It was observed that higher peak temperatures were associated with the 0.125 mm diameter beads than with the 0.075 mm or smaller diameter beads for those tests in which the test cigarette curled significantly upwards and away from the substrate surface. This is consistent with expectations of higher absorption of thermal radiation associated with the larger TC. A quantitative measure of the curling of cigarettes during testing was not made.)

As a result of these tests, all further temperature measurements were performed using 0.075 mm TCs. These offered the best combination of temperature accuracy and durability. Nonetheless, TC breakage did occur in some experiments. The TC beads were cleaned after each test using ethanol and a small paint brush. Thermocouples were only replaced upon breakage.

Two nonreactive configurations were used in the reference tests. In 1a, the cigarette was uncovered; in 1b, the cigarette was covered by a piece of UF-400 sheeting. [1]

5.2.2 Reactive Substrates

Conceptually, there were to be four configurations of reactive substrates. In two of the configurations, the substrate would consist of a piece of upholstery fabric on top of a block of a flexible polyurethane foam (FPUF). The block was nominally 203 mm x 203 mm x 50 mm thick. The TC collar described above would be placed on top, as shown in Figure 6. In performing the mattress ignition resistance tests in 16 CFR part 1632, half of the cigarettes are covered with a piece of UF-400 sheeting; in the other half, the cigarettes are uncovered. The presence or absence of this cover fabric results in two configurations. In the furniture tests cited earlier, the cigarette is placed in the crevice formed by two orthogonal blocks of fabric-covered foam. The cigarette is always covered with cotton sheeting. The crevice configuration used in this project is shown in Figure 7.[2] Note that the collar is hinged in the middle to fit in the crevice formed by the two blocks. It was recognized that testing with an uncovered cigarette might someday become desirable, but little project effort was expended in this direction.

Both for obtaining reference data and for subsequent screening of alternate ignition sources, there needed to be a sufficient amount of uniformly ignition-susceptible material for a large number of tests. Variations in the properties of FPUF can affect its smoldering performance [35], so the specimens were cut from a block of foam whose ignition uniformity had been previously examined. It was also necessary that an SRM 1196 cigarette ignite the fabric/foam substrate some, but not all, of the time in a series of replicate tests. To achieve this, various fabrics were tested over specimens of the foam, and an appropriate fabric was selected for each test configuration. Since the thermal environment in each configuration is different, it was not expected that a single fabric would emerge, and this was the case.

A typical test lasted approximately 40 min. The criteria for ignition were that the substrate was smoldering at the end of the test and/or the char extended at least 3 cm normal to the cigarette.

For the flat substrate with the cigarette uncovered, a preliminary screening of fabrics indicated that four tests each of a yellow and blue floral fabric and a blue diamond fabric (both supplied by CPSC staff), as well as a single layer of a heavyweight cotton denim, resulted in no ignitions.[3] Two layers of the denim fabric over the foam offered the potential for achieving some, but not 100 %, ignitions. A subsequent set of 20 tests resulted in five ignitions, confirming this expectation. This configuration was designated as 2a.

---

[1] This is the "standard" cover fabric used in all the cigarette ignition resistance tests. It is a white, non-fire-retarded, unlaundered, 100 % cotton bed sheeting material with an areal density of 125 ± 28 g/m^2 (3.7 ± 0.8 oz/yd^2).

[2] In both apparatus photographs, the upholstery fabric and cigarette orientation were chosen for visual effect.

[3] We found, as have others, that multiple batches of the "same" fabric do not necessarily lead to the same ignition susceptibility. Thus, we are not providing detailed specifications for the fabrics since they cannot be replicated for future testing. Sufficient information is provided to alert the reader when different fabrics are being incorporated into the substrates.

Four tests each of the same four substrates, with the cigarette covered by a sheet of UF-400 cotton sheeting, led to results similar to the uncovered experiments. The confirming set of 20 tests with two layers of the denim fabric resulted in 12 ignitions. This configuration was designated as 2b.

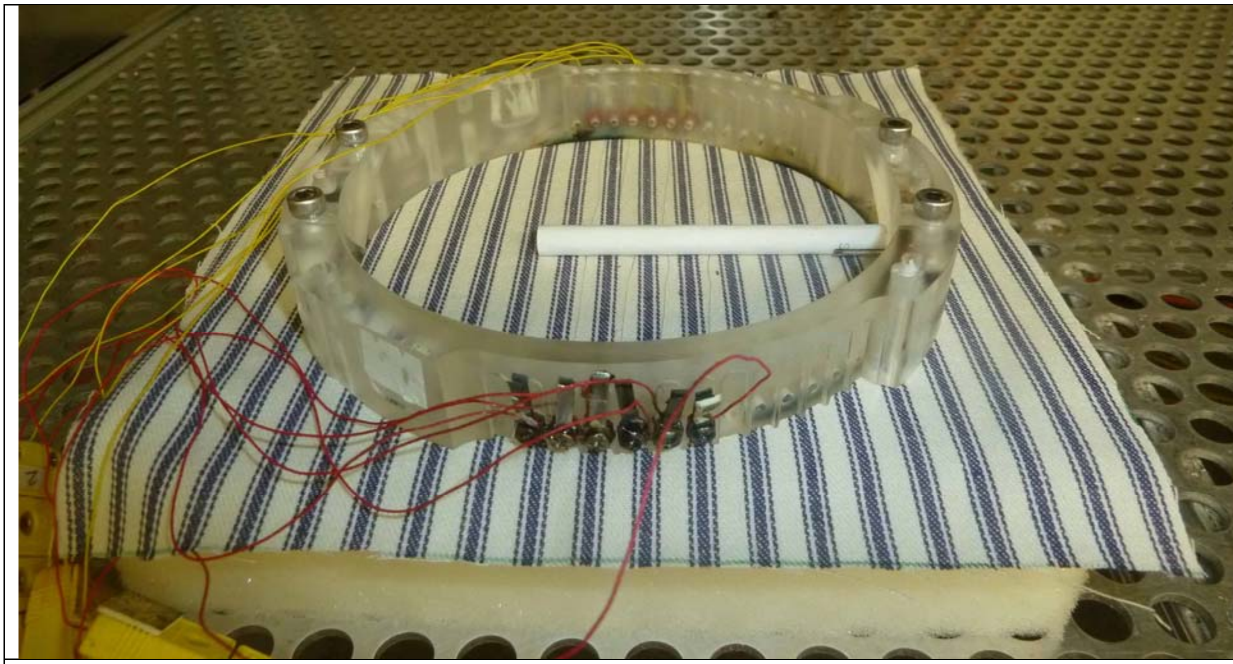


Figure 6. Photograph of Reactive, Flat Substrate with an SRM 1196 cigarette and Thermocouple Array.

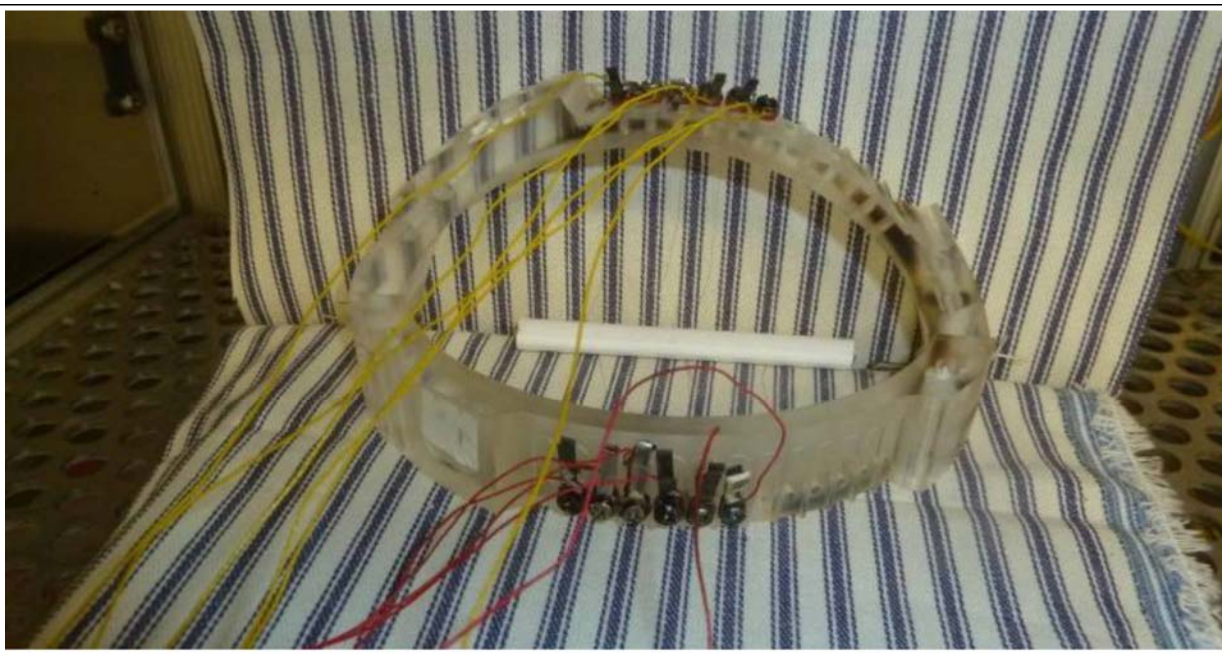


Figure 7. Photograph of Reactive Crevice Substrate with an SRM 1196 Cigarette and Thermocouple Array.

For the crevice substrate with the cigarette covered by the UF-400 sheeting, quadruplicate tests of the denim and floral fabrics resulted in all four substrates igniting. Tests with the UF-400 fabric under and over the cigarette resulted in no ignitions. Screening with the blue diamond fabric, with the cigarette oriented parallel to the stripes, resulted in two ignitions. (During preliminary tests with the cigarette oriented normal to the stripes, there was some curling of the fabric, which moved the cigarette. This was less a problem with the cigarette positioned parallel to the stripes.)

In summary, the SRM 1196 reference testing was performed in three reactive configurations:

> 2a. Flat surface, with the cigarette uncovered. A substrate consisting of two layers of a heavyweight cotton denim fabric on top of the foam block was found to ignite some, but not, all of the time when a lit SRM 1196 cigarette was placed on top of it. The foam was from the same batch used in the 1992 round robin of the Mock-up Ignition Test Method under the Fire Safe Cigarette Act of 1990 [36]. Tests conducted in 2001 indicated that the contribution of the foam to substrate ignition susceptibility was nominally unchanged [37].
>
> 2b. Flat surface, same materials as 2a, but with the cigarette covered with UF-400 sheeting.
>
> 3. Covered cigarette in the crevice location. The upholstery fabric was a single layer of a lightweight, blue-striped cotton. The foam was the same type as was used in the flat configuration.

As noted at the beginning of this section, because there is no standard testing performed with an uncovered cigarette in the crevice, this configuration was not pursued.

5.3 Reference Data

Replicate tests were performed because of the experimental variability noted in Section 5.2. There were multiple sources of this variability. (a) These fine TCs were not perfectly straight, so the bead locations relative to each other and their thermal contract with the substrate could vary. (b) The cigarette ash distorted in an inconsistent way, changing the thermal contact of the cigarette with the substrate and the TC junction. (c) The fabric surface was not perfectly smooth. The number of replicates was varied with experience and the needed degree of precision.

The laboratory room was maintained at (23 ± 3) °C and (55 ± 3) % relative humidity. Test specimens and cigarettes were conditioned in the room for at least one day.

5.3.1 Inert Substrate

Cigarette Uncovered

We conducted 180 experiments of uncovered SRM 1196 cigarettes on the inert substrate. Two examples of the temperature profiles are given in Figure 8, where the different curves correspond to different TCs. These two plots indicate the degree of variability seen in the replicate experiments. Note also that the curves are not always smooth, and all the peaks are not always the same shape. Nonetheless, in nearly all cases, we were able to extract the peak temperature from these data.

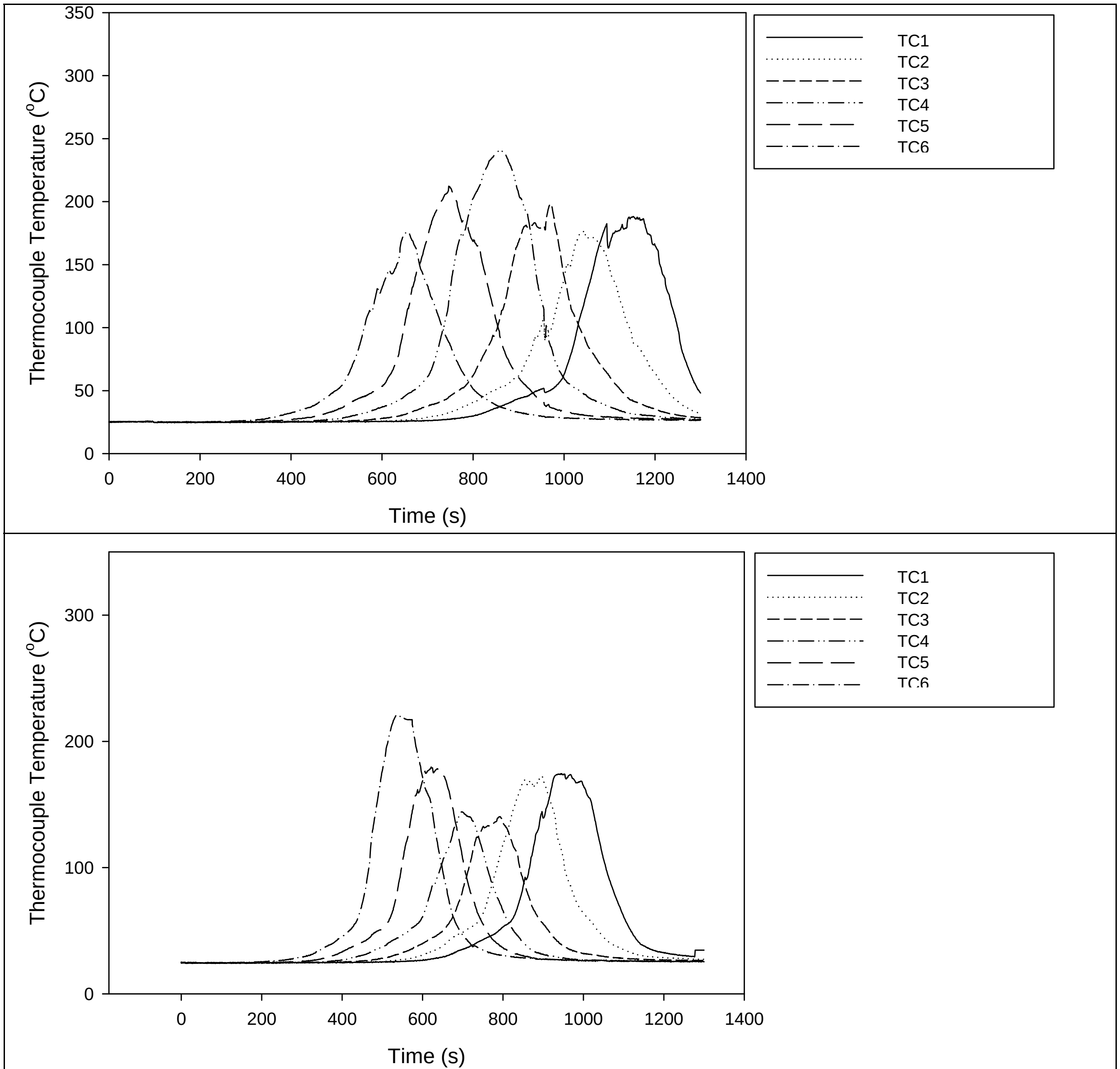


Figure 8. Temperature Measurements for Two Tests of Uncovered SRM 1196 Cigarettes on the Inert Substrate.

A histogram of peak temperatures for the same configuration is plotted in Figure 9. The peak temperatures measured for all the TCs have been grouped into bins or clusters. For example, all peak values between 92 °C and 108 °C were placed in the cluster located at 100 °C on the abscissa. At this location are six bars, each bar corresponding to one thermocouple location. The leftmost bar represents the reading from TC1, the next is from TC2, etc. The height of each bar represents the number of times that a thermocouple “saw” this temperature in *all* the experiments. Note that there is no pattern of peak heights among the thermocouples, e.g., no thermocouple consistently measured higher temperatures than the others.

The seventh (and much taller) bar is the sum of the other six bars; it is the frequency with which all TCs measured peak temperatures in this range. These bars appear to approximate a normal distribution that is modestly skewed toward to high temperature side. The mean peak temperature and standard deviation in this configuration are approximately 190 °C ± 30 °C. However, this may be misleading in terms of interpreting the potential for ignition. Both the rate of heat transfer from the cigarette to the substrate and the rate of degradation of the substrate (if the substrate materials were organic) are temperature dependent. Thus, the higher peak temperatures are likely more influential in the ignition process than the lower peak temperatures.

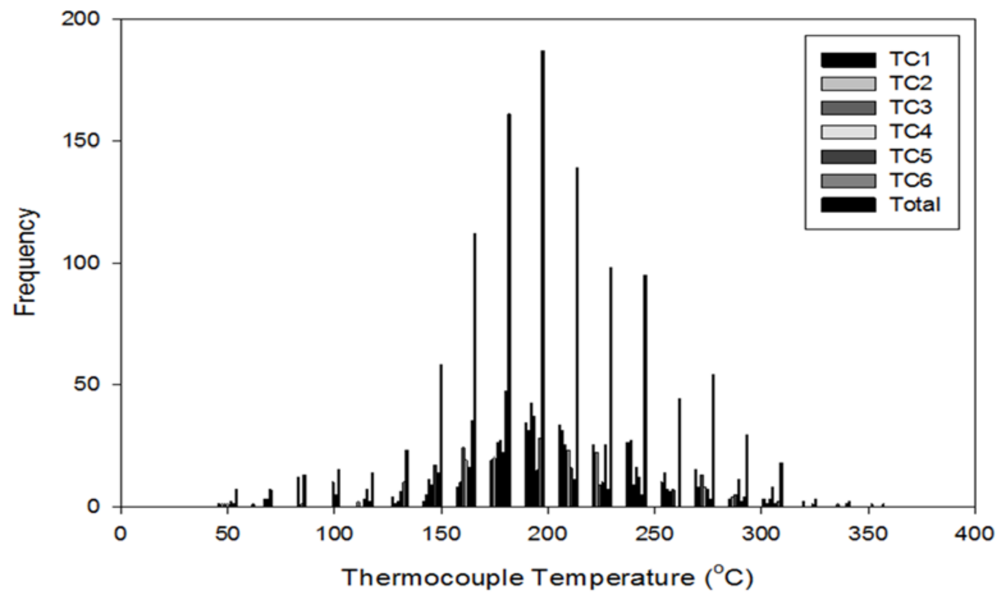


Figure 9. Distribution of Peak Temperature Measurements for Uncovered SRM 1196 Cigarettes on the Inert Substrate.

The linear burning rate of the cigarette was inferred by dividing the distance between two adjacent TCs (4 mm) by the difference in time at which these two TCs reach their peak temperatures, e.g., from Figure 8. The results of such calculations for the SRM 1196 cigarette over the inert substrate are plotted as a histogram in Figure 10 for experiments with the flat, uncovered configuration. The modal burning rate in this Figure is approximately 0.05 mm/s, which is comparable to literature values for smolder velocity in cellulosic materials [38].

The length of the heated coal of the cigarette was estimated by multiplying the linear burn rate by the width of a thermocouple curve from, e.g., Figure 8. This width was defined as the time interval bounded by the rising and falling sections of the temperature curve being at 100 °C. Figure 10 is a histogram of the relative frequency of these estimated coal lengths. As above, in each cluster, the leftmost bar represents the reading from TC1, the next is from TC2, etc. The ordinate height is in arbitrary units. The seventh bar was calculated using the difference between TC1 and TC6. The preponderance of coal lengths was within the interval 9 mm ± 2 mm.

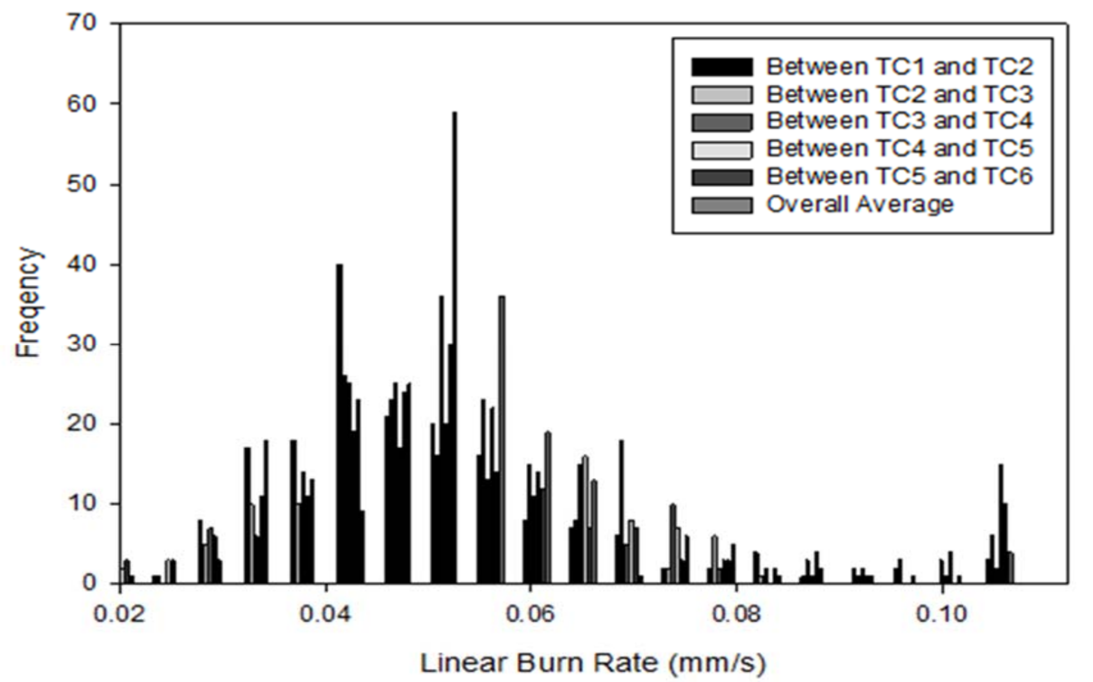


Figure 10. Distribution of Measured Linear Burn Rates for uncovered SRM 1196 Cigarettes on the Inert Substrate.

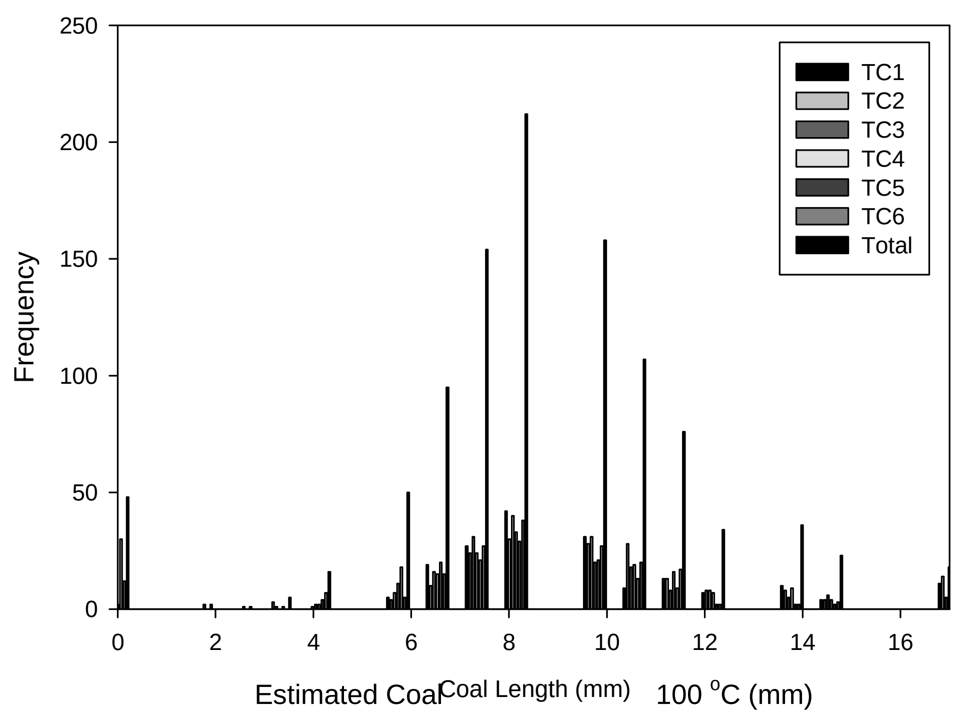


Figure 11. Distribution of Estimated Cigarette Coal Lengths (mm) between 100 °C Points for Uncovered SRM 1196 Cigarettes on the Inert Substrate.

Cigarette Covered

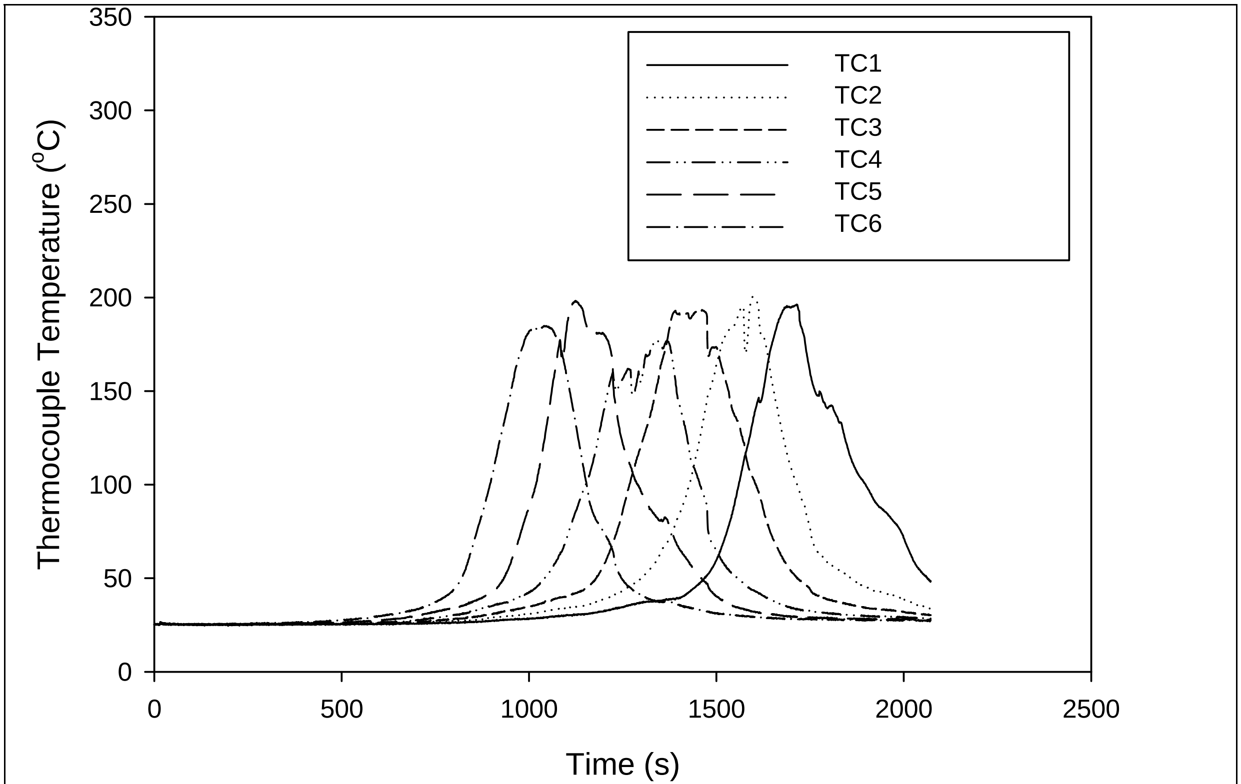
We conducted 60 experiments of covered SRM 1196 cigarettes on the inert substrate. In 16 of these, the cigarette extinguished before the cigarette coal reached the thermocouples. In nine experiments, the cigarette extinguished within the area monitored by the TCs. In the remaining 35 experiments, each cigarette burned its full length.

Two examples of the temperature profiles are given in Figure 12, where the different curves in each plot correspond to the different TCs. These two plots indicate the nature of the variability seen in the replicate experiments. Note also that the curves are not always smooth, and all the peaks are not always the same shape.

A histogram of peak temperatures (in clusters) for the same configuration is plotted in Figure 13. The “Total” bars appear to approximate a normal distribution, with perhaps a slightly longer tail toward the low temperature side. The mean peak temperature and standard deviation in this configuration are approximately 190 °C ± 30 °C.

Figure 14 shows the distribution of linear burning rates of the covered cigarettes, inferred by dividing the distance between two adjacent TCs (4 mm) by the difference in time at which these two TCs reach their peak temperatures. The modal burning rate in this Figure is approximately 0.035 mm/s, which is slower than the values for the uncovered cigarettes.

Figure 15 shows the distribution of lengths of the heated coal of the cigarettes. This width was again defined as the time interval bounded by the rising and falling sections of the temperature curve being at 100 °C. The “Total” peaks do not appear to approximate a normal distribution. The preponderance of coal lengths is within the interval of 9 mm ± 3 mm, similar to the uncovered cigarettes on the same surface.



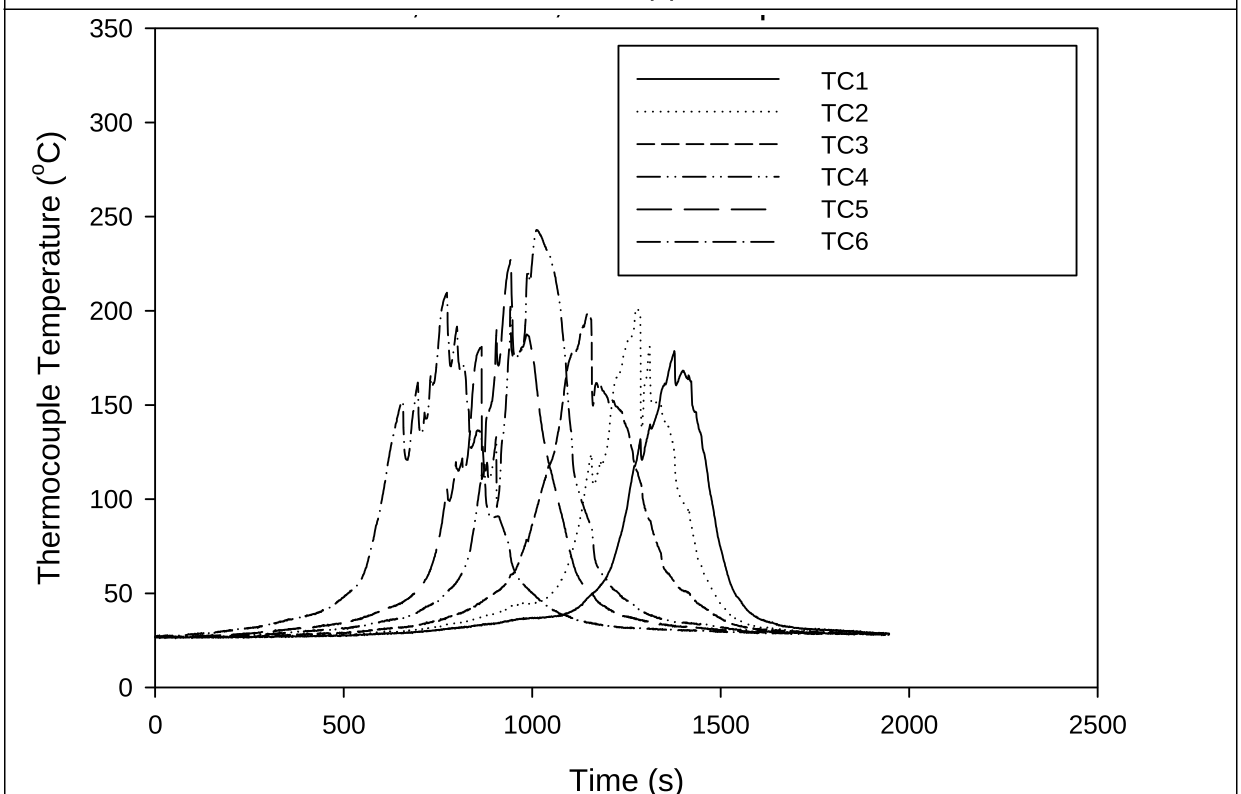


Figure 12. Temperature Measurements for Two Tests of Covered SRM 1196 Cigarettes on the Inert Substrate.

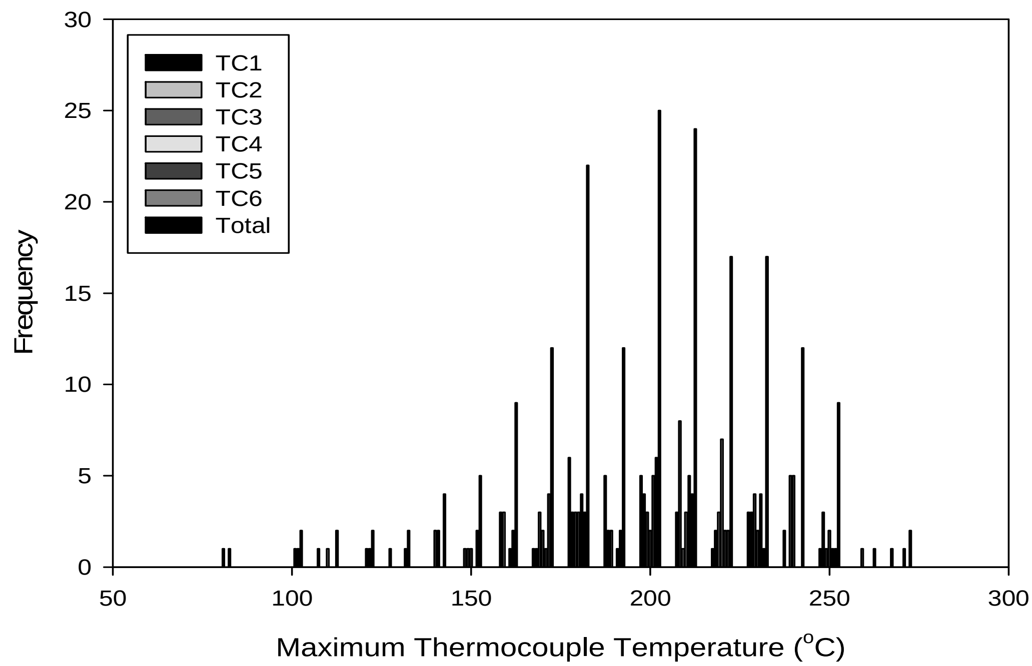


Figure 13. Distribution of Peak Temperatures for Covered SRM 1196 Cigarettes on the Inert Substrate.

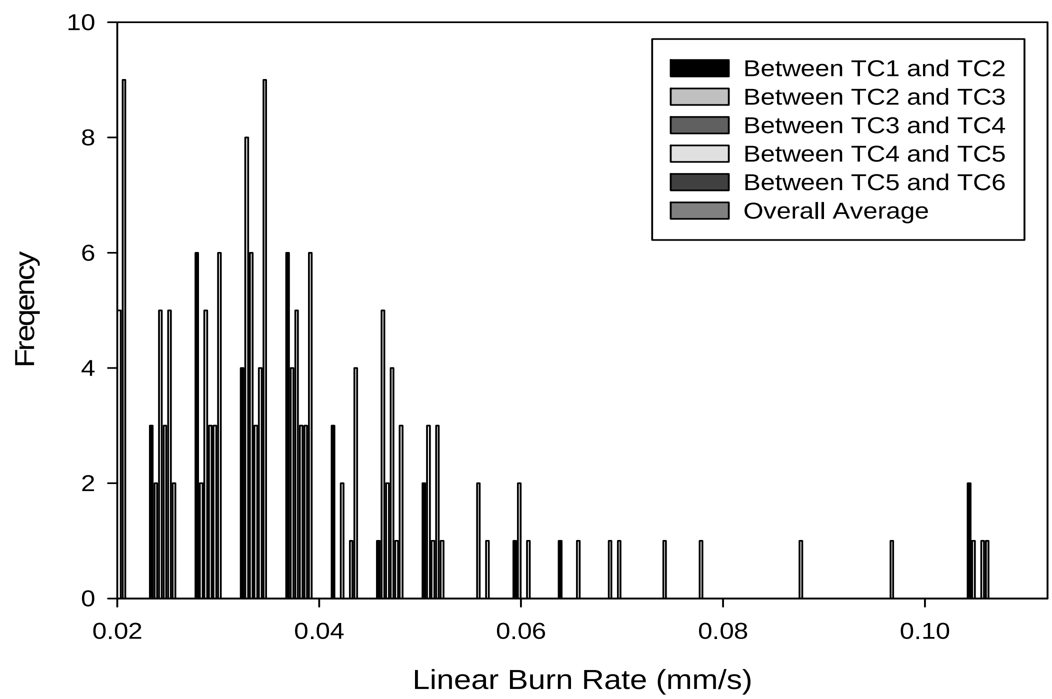


Figure 14 Distribution of Measured Linear Burn Rates for Covered SRM 1196 Cigarettes on the Inert Substrate.

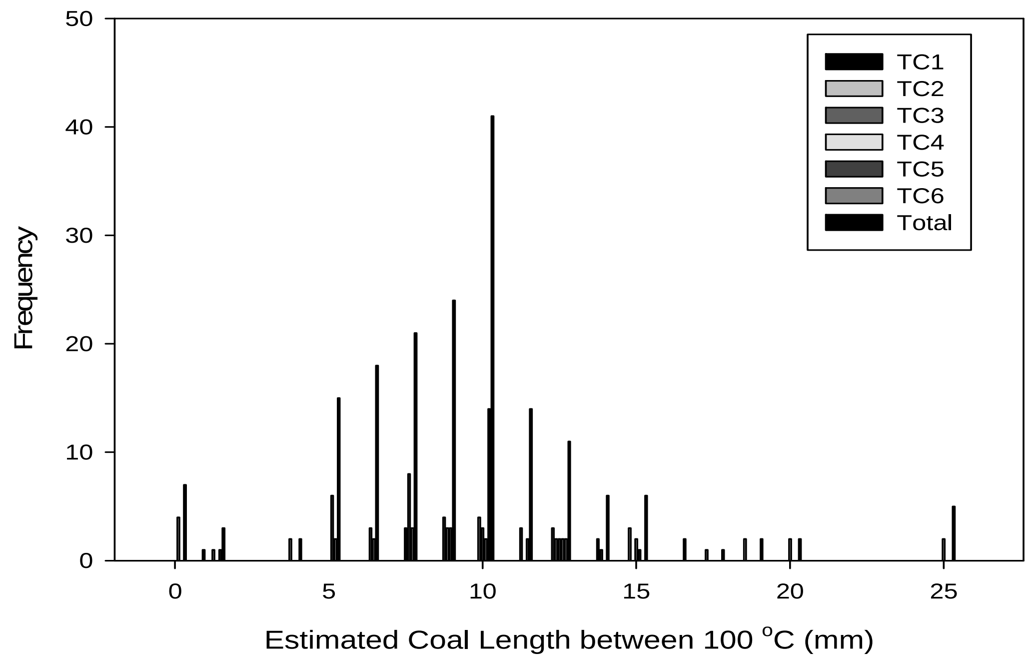


Figure 15. Distribution of Estimated Cigarette Coal Lengths (mm) between 100 °C Points for Covered SRM 1196 Cigarettes on the Inert Substrate.

5.3.2 Reactive Substrate: Flat, Cigarette Uncovered

Twenty experiments with this configuration were performed, and all 20 cigarettes burned their full lengths. Sustained ignition, which occurred in five of the experiments, was determined by visible char length, which sometimes was not conclusive until after the cigarettes had burned past the thermocouples. We used a criterion of smoldering extending 5 cm from the cigarette, observing that the burning cigarette no longer influenced the smoldering in the substrate. Charring that had reached this distance continued to expand in those experiments where we allowed the additional time.

The temperature measurements for two typical experiments are plotted in Figure 16. In the upper plot, the cigarette generated almost identical temperature profiles and peak temperatures at all six TC positions. Following each peak, all six TC temperatures returned to the ambient level. Nine of the 20 experiments showed this kind of behavior. Two resulted in ignitions.

In the lower plot, the behavior was quite different. After the coal passed the first thermocouple (TC6), this temperature decreased and then rose to a second peak near 1000 s. The same behavior is observed for the next four thermocouples. The substrate had begun generating heat even before the cigarette coal had passed the thermocouple array. (The sharp peaks at 1600 s are spurious; they occurred as the substrate was being dismantled before flaming might occur.)

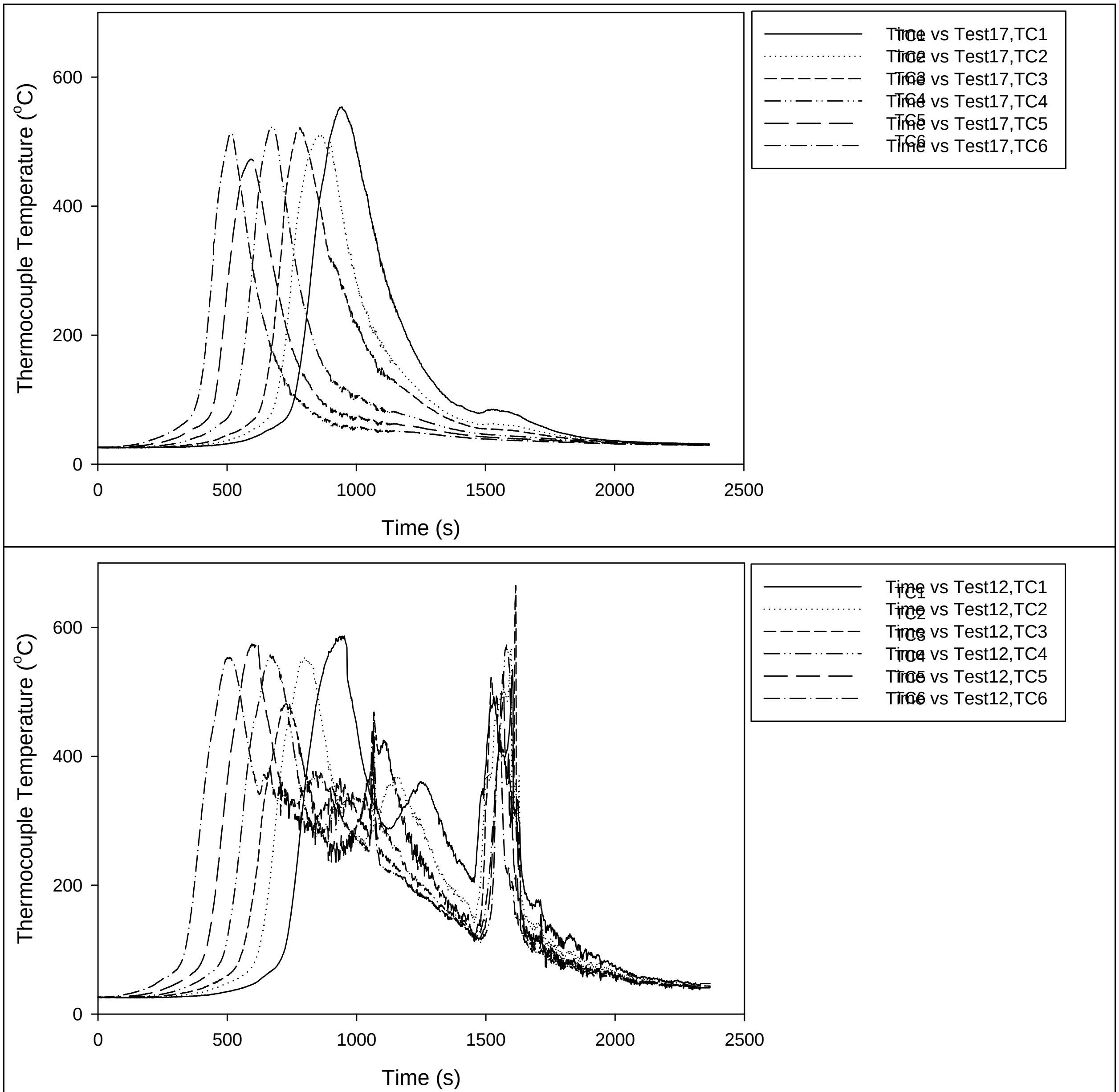


Figure 16. Temperature Measurements for Two Tests of an Uncovered SRM 1196 Cigarette on a Flat, Reactive Substrate.

A histogram of the measured peak temperatures is provided in Figure 17. The peak temperatures occurred prior to sustained substrate ignition. The upper plot is for all 20 experiments. The distribution approximates a normal distribution with a mean and standard deviation of 570 °C ± 20 °C. The lower plot is for the five experiments in which ignition occurred. Since ignition occurred after the coal had passed each TC, there was no significant difference in distribution between igniting and non-igniting substrates.

Linear burn rates, calculated in the same manner as for the inert substrate, are shown in Figure 18. The upper plot is for all 20 experiments; the lower plot is for the five experiments that resulted in ignitions. There is no significant difference between the two distributions for the same reason as with the peak temperatures. The preponderance of linear burning rates is within the interval 0.06 mm/s ± 0.02 mm/s.

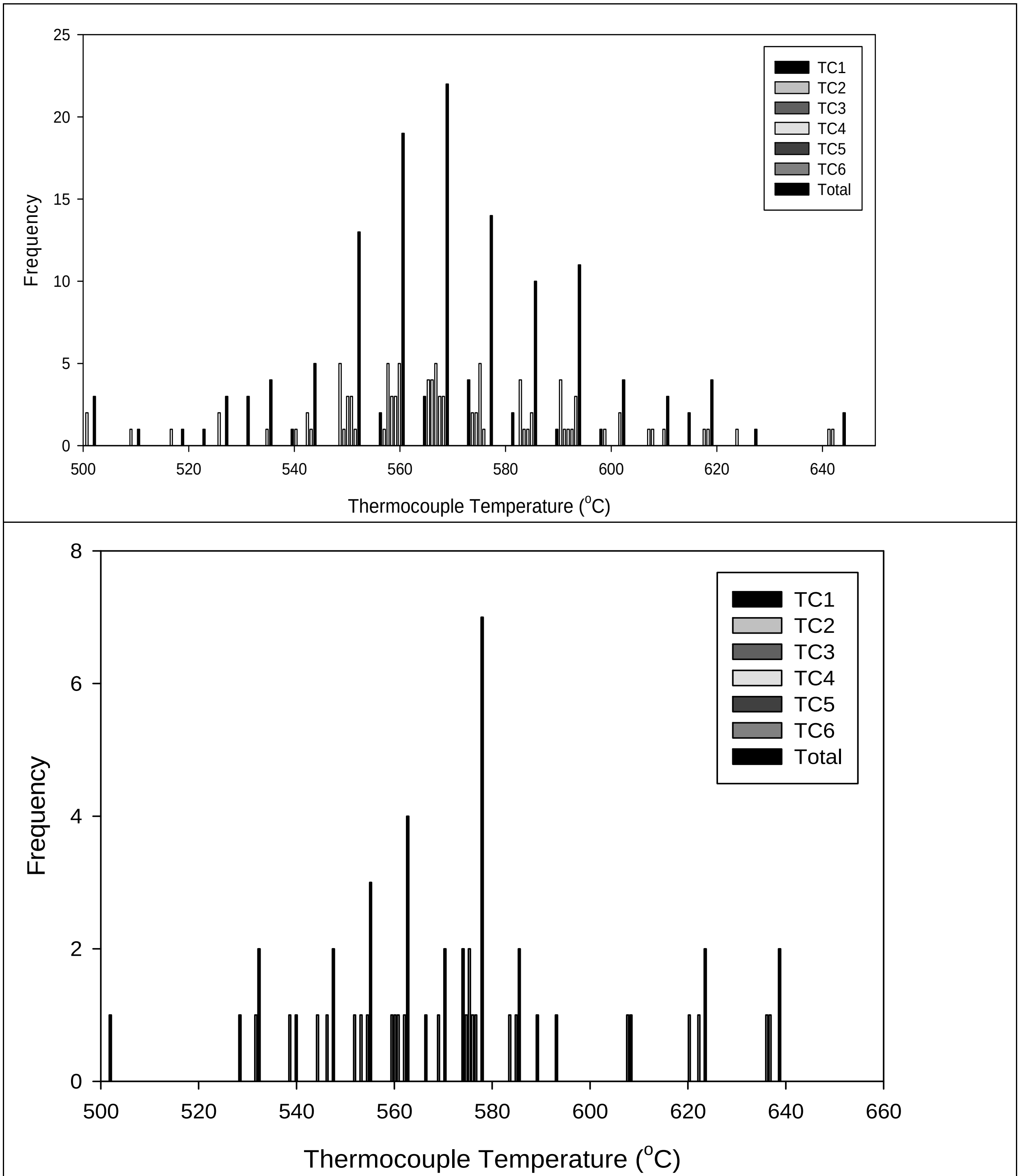


Figure 17. Distribution of Peak Temperature Measurements for Uncovered SRM 1196 Cigarettes on the Flat, Reactive Substrate; top: all experiments; bottom: substrates that ignited.

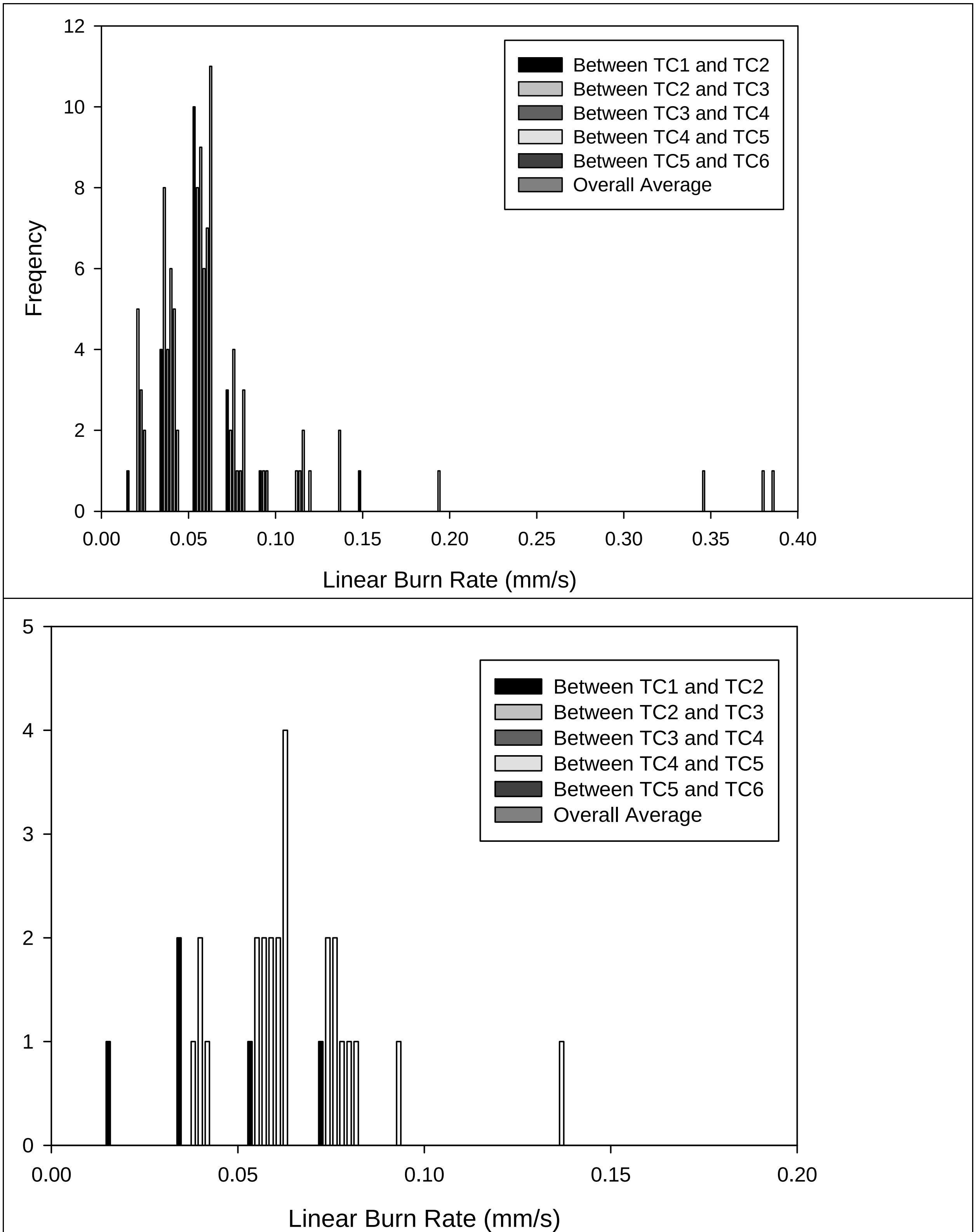


Figure 18. Distribution of Measured Linear Burn Rates for Uncovered SRM 1196 Cigarettes on the Flat, Reactive Substrate; top: all experiments; bottom: substrates that ignited.

In many of the plots, some or all of the peak shapes were irregular, making it difficult to estimate peak widths (at the 100 °C points) on a uniform basis and thus estimate cigarette coal lengths. We estimated that the coal lengths were generally on the order of 25 mm.

5.3.3 Reactive Substrate: Flat, Cigarette Covered

Similar measurements were obtained for 20 experiments in which an SRM 1196 cigarette was placed on a flat, reactive (ignitable) fabric/foam substrate and covered with a piece of UF-400 sheeting. Twelve of these experiments resulted in substrate ignition. In all but one experiment, the cigarette burned its full length.

The temperature measurements for two typical experiments are plotted in Figure 19. In the upper plot, the cigarette generated almost identical temperature profiles and peak temperatures at all six TC positions. Following each peak, all six TC temperatures returned to the ambient level. Seventeen of the 20 experiments showed this kind of behavior. Nine resulted in ignitions.

In the lower plot, an early ignition has occurred. After the cigarette coal passed the first four thermocouples (TC6 through TC3), their temperatures decreased and then rose near 1100 s. The substrate had begun generating heat even before the cigarette coal has passed the thermocouple array. This behavior was observed in only three of the experiments, each resulting in sustained ignition.

A histogram of the measured peak temperatures is provided in Figure 20. The peak temperatures occurred prior to sustained substrate ignition. The upper plot is for all 20 experiments. The distribution might be bimodal, but in any event cannot be presumed to follow a normal distribution. The preponderance of the temperatures is within the interval 570 °C ± 30 °C.

The lower plot is for the eight experiments in which ignition did <u>not</u> occur, although there was some *temporary* smoldering. The peak temperatures are centered slightly (probably not significantly) higher than the overall set, with the preponderance near 600 °C ± 25 °C.

The distributions of linear burn rates are shown in Figure 21. The upper plot is for all 20 experiments; the lower plot is for the eight experiments that did <u>not</u> result in ignitions. The preponderance of linear burning rates is within the interval 0.06 mm/s ± 0.02 mm/s.

As with the data from the uncovered cigarette experiments, in many of the plots, some or all of the peak shapes were irregular, making it difficult to estimate peak widths (at the 100 °C points) on a uniform basis and thus estimate cigarette coal lengths. A rough estimate is that the coal lengths were on the order of 35 mm.

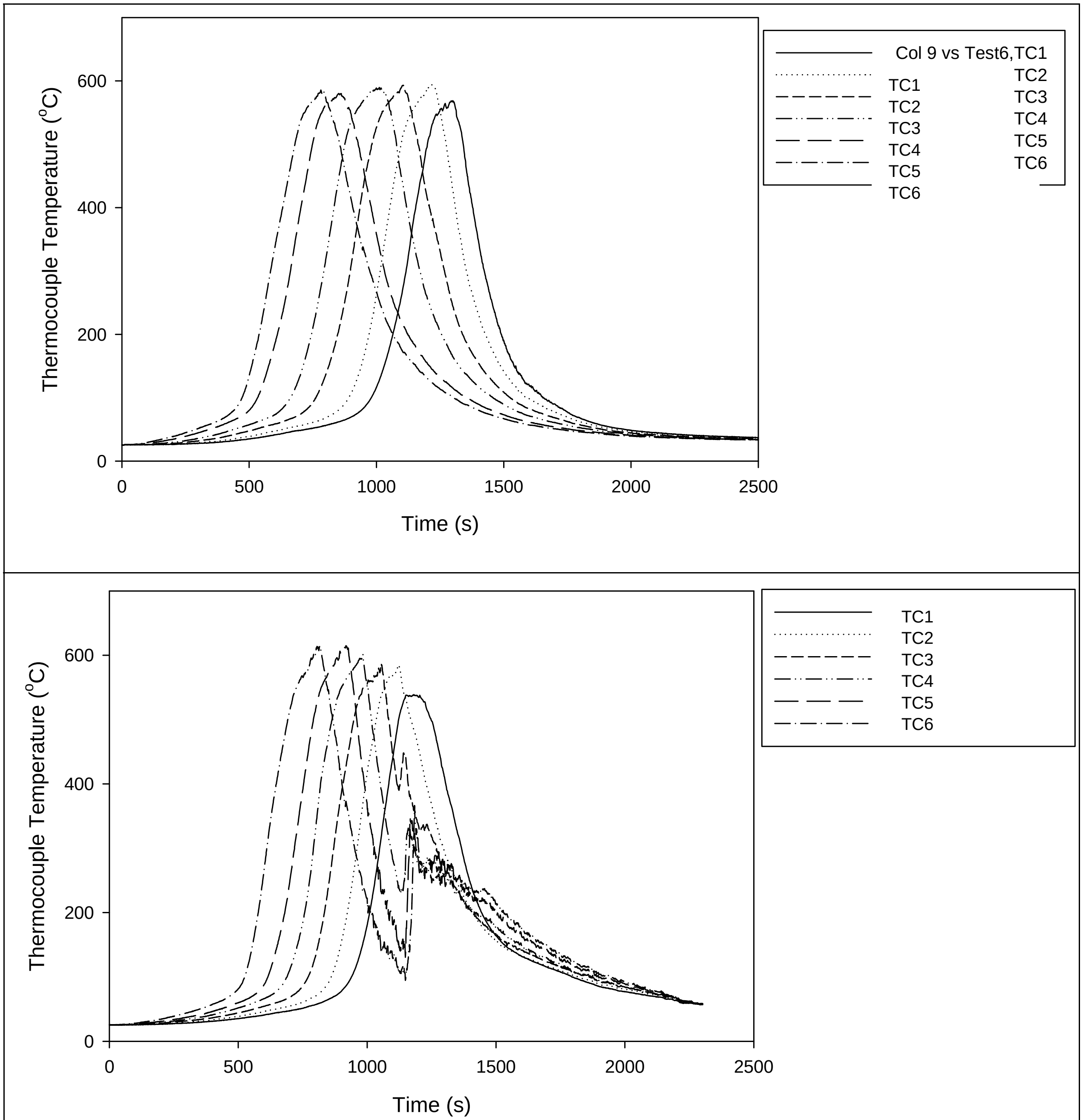


Figure 19. Temperature Measurements for Two Tests of a Covered SRM 1196 Cigarette on a Flat, Reactive Substrate.

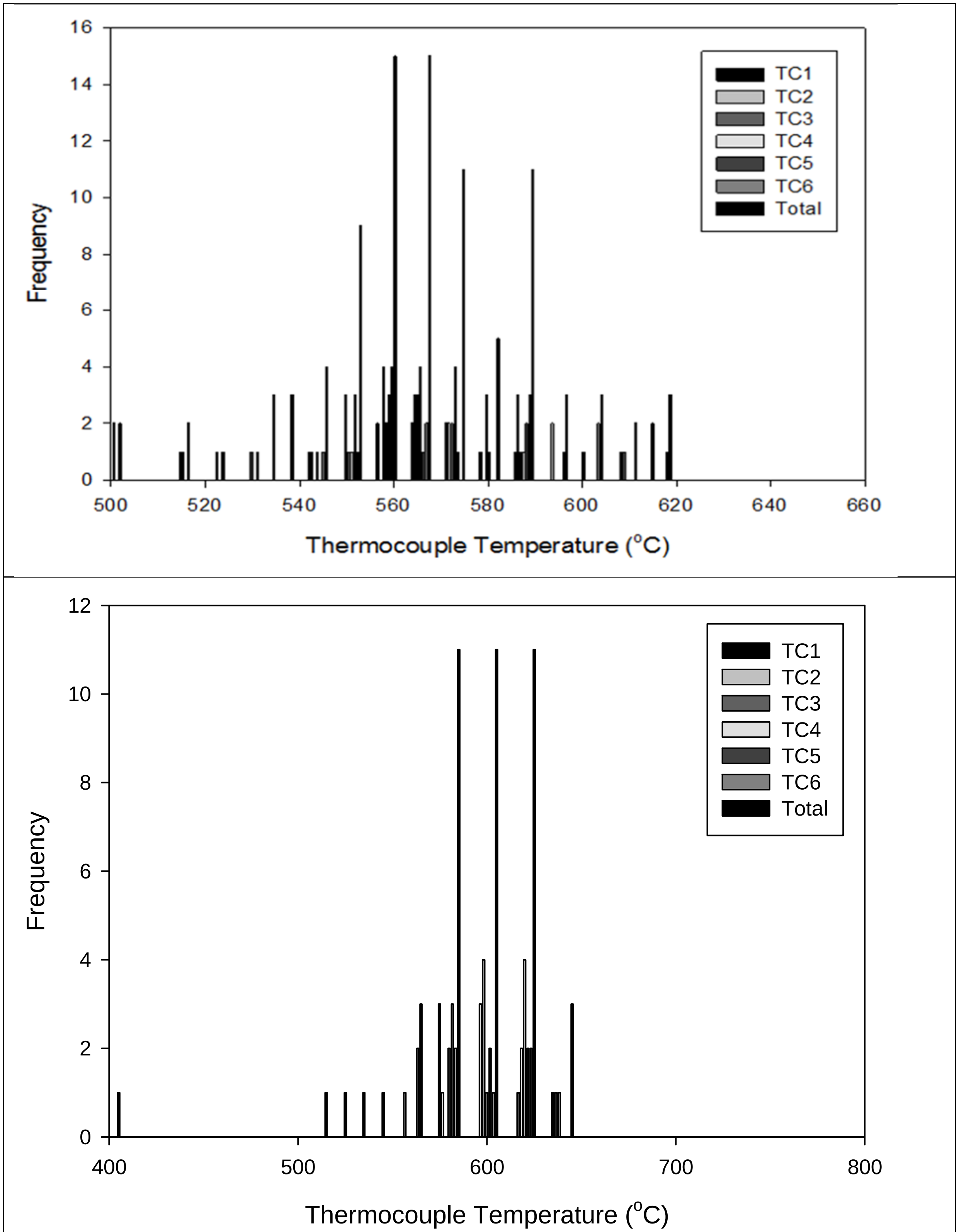


Figure 20. Distribution of Peak Temperature Measurements for Covered SRM 1196 Cigarettes on the Flat, Reactive Substrate; top: all experiments; bottom: substrates that did not ignite.

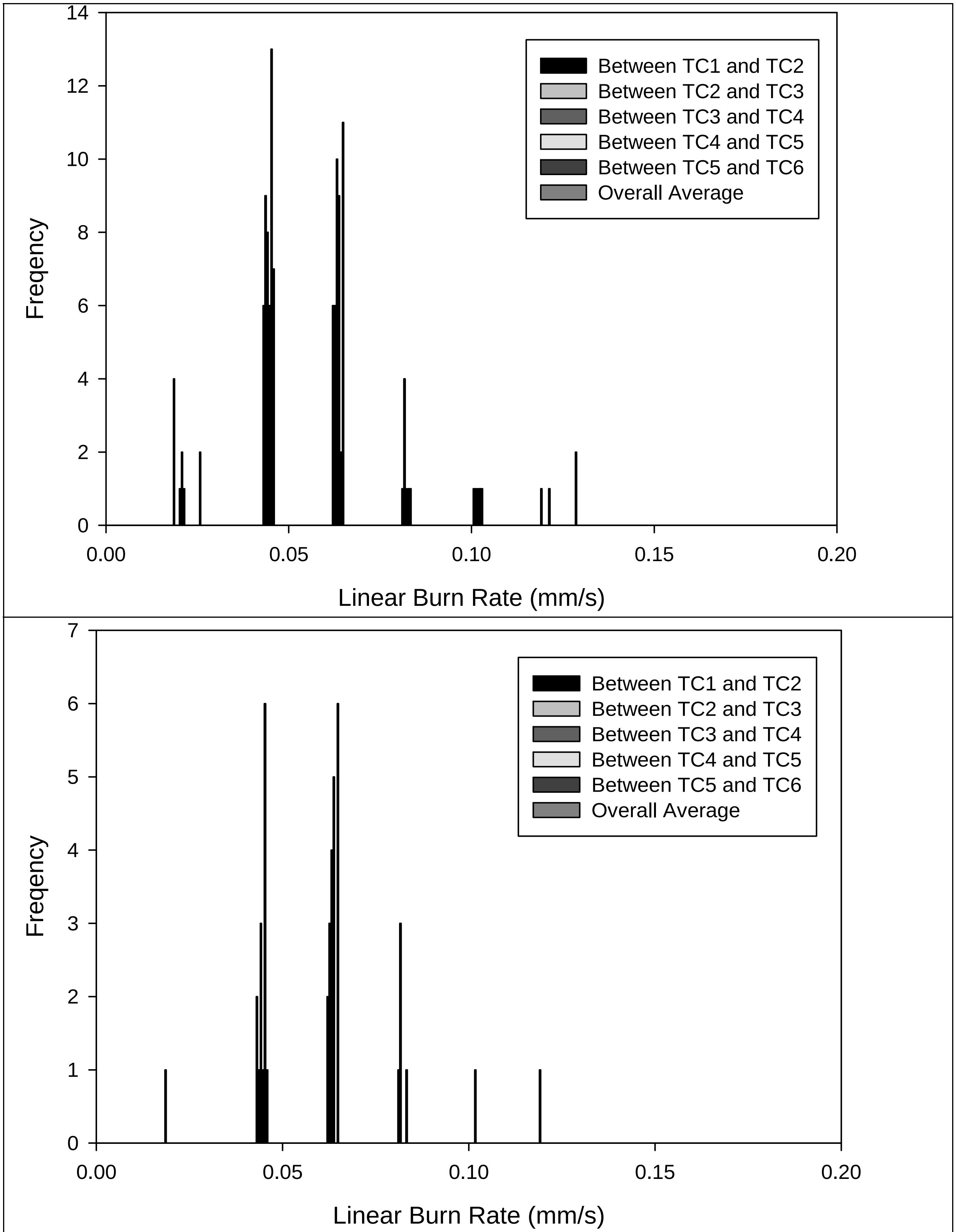


Figure 21. Distribution of Measured Linear Burn Rates for Covered SRM 1196 Cigarettes on the Flat, Reactive Substrate; top: all experiments; bottom: substrates that did not ignite.

5.3.4 Reactive Substrate: Crevice, Cigarette Covered

Twelve experiments were performed in which an SRM 1196 cigarette was placed in the crevice of a reactive (ignitable) fabric/foam substrate and covered with a piece of UF-400 sheeting. Two of these experiments resulted in substrate ignition.

Thermocouple temperatures for two of these crevice tests are plotted in Figure 22. The peak temperatures are notably lower than those for the experiments on the flat, reactive substrate. (In both frames, the highest peak temperatures are approximately 100 °C below those in Figure 19 and are at the lowest values shown in Figure 20.) The upper plot shows the result of a non-ignition. As the cigarette continued to burn, the temperature peaks became wider, likely as a result of the heat being trapped by the cover sheet. The bumps in the temperature curves at approximately 1800 s might indicate that a small amount of substrate smoldering had been initiated. However, the return of all the TC profiles to near ambient temperatures indicates that the ignition was not sustained. The lower plot depicts an experiment in which ignition occurred. That possibly unsustained ignition in the lower plot has established itself, and the TC profiles rise until it was necessary to quench the substrate. Note that in both plots, TC4 and TC6 registered peak temperatures near 200 °C. This suggests that the beads in these TCs might have been out of position relative to the path of the cigarette coal.

Figure 23 shows the distribution of peak temperatures. The values between 200 °C and 250 °C are all from TC2 and TC4. The remaining four thermocouples registered peak values that are spread over a range of 250 °C, with a preponderance of the values in the range 430 °C ± 40 °C.

The distribution of linear burn rate measurements is given in Figure 24. Note that, in this plot, the rightmost bar is the *average* of the other five bars rather than the *sum*, as in the previous such plots. The bar height was rounded to the nearest integer, including zero. There is significantly more scatter in the burning rate measurements for the crevice test as compared to other scenarios. The cause of this increased variability was not established, but it is known that the burn rate is very sensitive to the oxygen availability which is itself sensitive to the width of any air gap between the two foam blocks that constitute the crevice substrate. The preponderance of values is in the range 0.02 ± 0.01 mm/s.

As can be seen in Figure 22, when ignition occurred, the temperature profiles generally did not return to 100 °C, making it impossible to determine a coal length. When ignition did occur, the temperature peaks were quite elongated, which was consistent with the slow linear burn rate of the cigarette coal. For these experiments, a rough estimate is that the coal lengths were on the order of 35 mm.

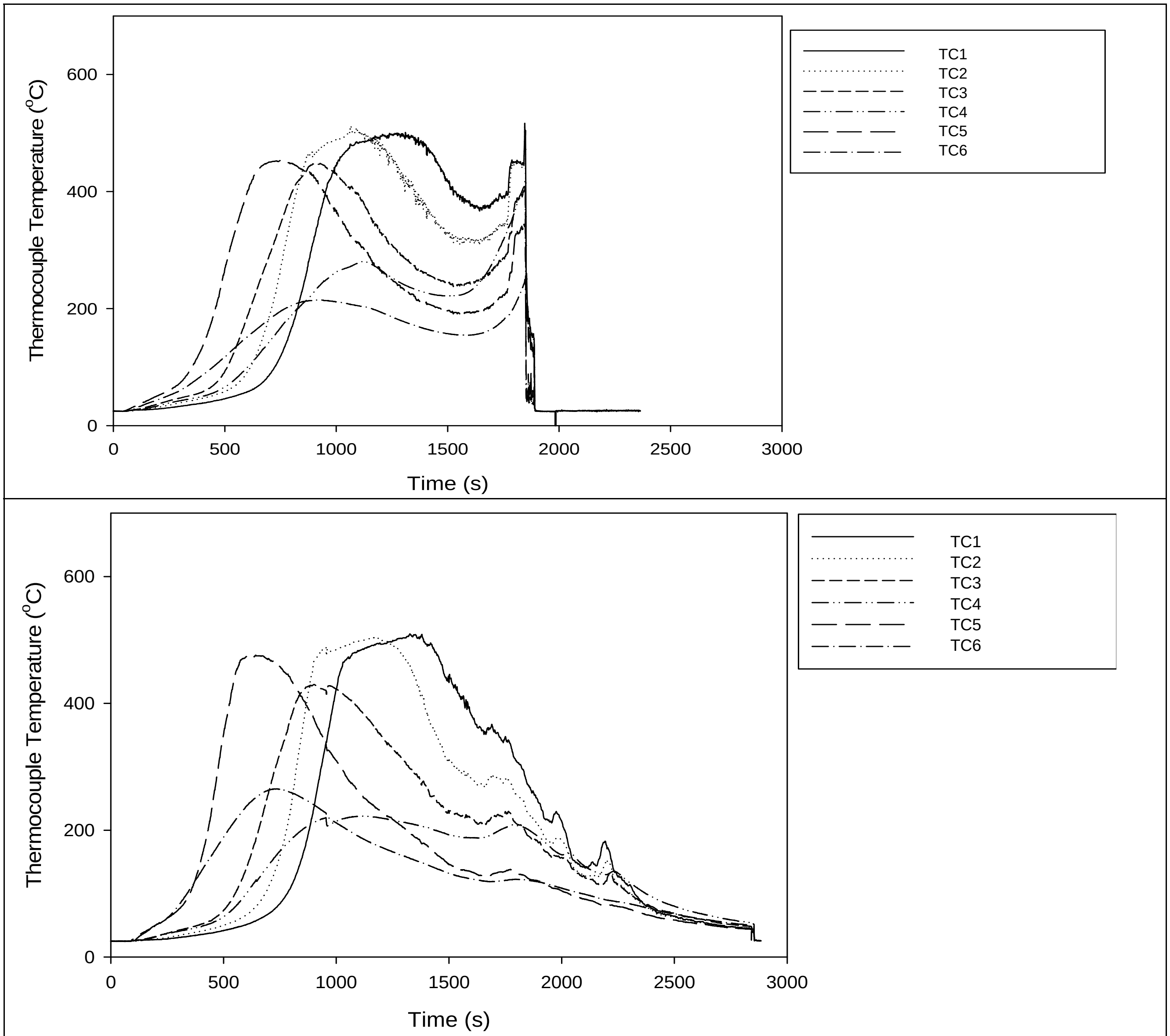


Figure 22. Temperature Measurements for Two Tests of a Covered SRM 1196 Cigarette on the Reactive Crevice Substrate.

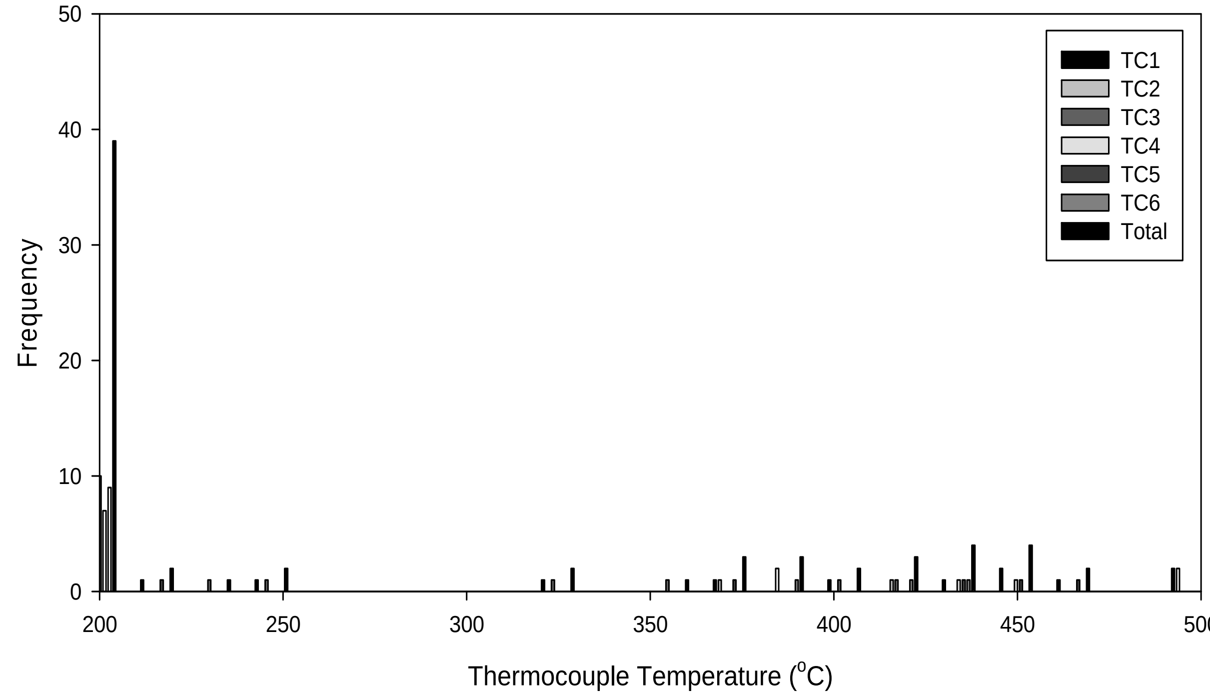


Figure 23. Distribution of Peak Temperature Measurements for Covered SRM 1196 Cigarettes on the Reactive Crevice Substrate.

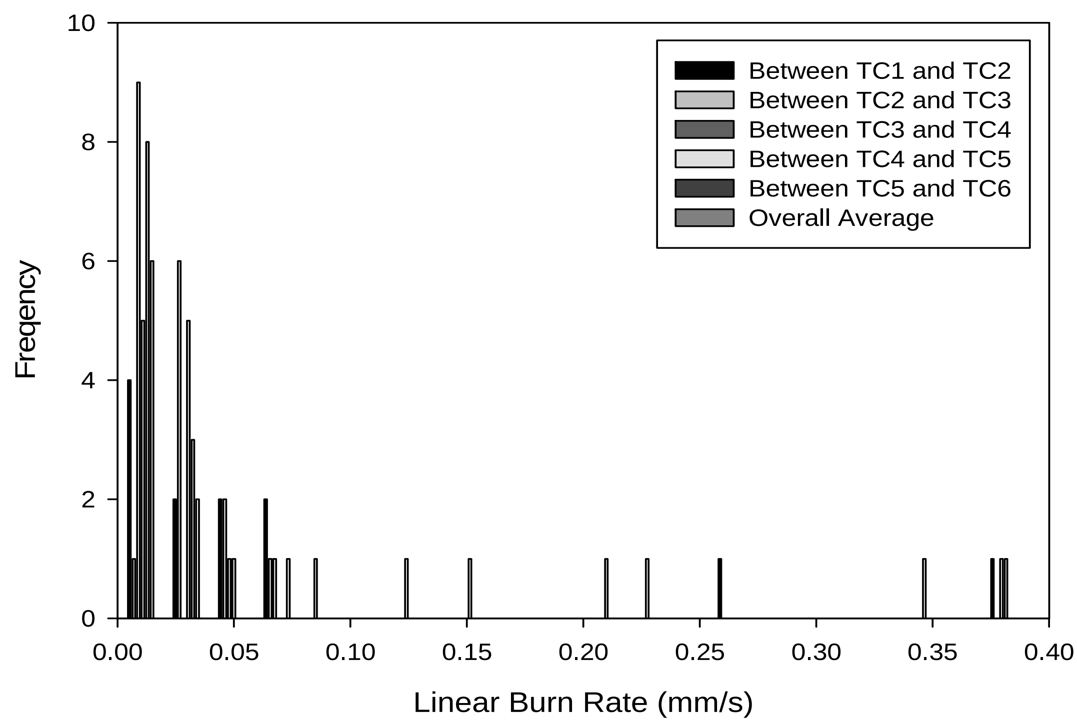


Figure 24. Distribution of Measured Linear Burn Rates for Covered SRM 1196 Cigarettes on the Reactive Crevice Substrate.

5.4 Summary of SRM 1196 Reference Data

Table 2 summarizes the data from Section 5.3.

Table 2. Summary of SRM 1196 Cigarette Reference Data.

Substrate			Peak T (°C)	Linear Burn Rate (mm/s)	Coal Length (mm)
Inert	1a	Cigarette uncovered	190 °C ± 30 °C	0.05 ± 0.01	9 ± 2
	1b	Cigarette covered	190 °C ± 30 °C	0.035 ± 0.015	9 ± 3
Reactive	2a	Flat, uncovered	570 °C ± 20 °C	0.06 ± 0.02	*ca.* 25
	2b	Flat, covered	570 °C ± 30 °C	0.06 ± 0.02	*ca.* 35
	3	Crevice, covered	430 °C ± 40 °C	0.02 ± 0.01	*ca.* 35

There are several observations:

- The peak cigarette/substrate interface temperatures measured for the SRM 1196 cigarette on the reactive substrates were consistent with published values, although those prior values were obtained using other cigarettes and other fabric/foam substrates.
- The peak temperatures on the inert substrate were significantly lower than those on the reactive substrates. This was due to the far higher thermal inertia of the brass plate compared to that of the fabric/foam composition of the reactive substrates.
- There are three benefits of the thermal measurements of candidate ignition sources on the inert substrate.
    - They provide information on the heat output from the source without complications arising from thermal feedback from a possibly reacting substrate.
    - The histograms of peak temperatures, linear burn rate, and coal lengths provide indicators of the best possible repeatability.
    - These data can be used to refine the ignition source and to "calibrate" batches for routine testing.

  Should these values become pivotal to the use of the final selection of ignition source(s), new experiments would be performed with a substrate with thermal inertia comparable to those of fabric/foam substrates.
- Covering the cigarette did not appear to have a significant effect on the peak interface temperature.
- The interface temperatures in the covered, crevice ignition experiments were approximately 100 °C lower than their covered counterparts on the flat substrate.
- The linear burn rate of the uncovered cigarettes was not significantly different for the two substrates. This suggests that the linear burn rate was driven more by the interior temperature of the cigarette than the interface temperature.
- Covering the cigarette on the inert substrate reduced the linear burn rate, while there was no effect of covering in the experiments on the flat reactive substrate.

- The typical linear burn rate for a covered cigarette in a crevice was the lowest of any of the configurations.
- The coal lengths for cigarettes burning on the reactive substrates were notably longer than those burning on the inert substrate. These high values were used to guide the dimensions of the candidate surrogate ignition sources as reported in Section 6.
- Nearly all the observed ignitions resulted in elevated surface temperatures minutes after the cigarette coal had passed. This indicates that the substrate was heated high enough and over a sufficient time interval to initiate smoldering and that the smoldering front often grew quite slowly toward the location of the thermocouples.

Taken together, these results suggested that examination of specific candidate ignition sources

- Be conducted principally on reactive substrates and
- Take into account the time/temperature profile of the ignition source.

6 SCREENING OF CANDIDATE SUFFOGATE IGNITION SOURCES

6.1 General Approach

Based on the findings from the literature survey and extensive discussions, we considered a number of representatives of three types of heat sources: externally powered sources, locally or self-powered sources, and passive (pre-heated) sources. The latter two groups eliminate the tethering difficulties caused by electrical leads.

Prior to any testing, each potential source was analyzed for feasibility, safety, and perhaps cost. The analysis eliminated some candidates from any laboratory experiments. For other candidates, the analysis provided guidance as to the experimental parameters for their operation.

The representatives were examined in three configurations which were similar to some used in Section 5.2:

> <u>Configuration 1a</u>: The same flat, inert substrate, ignition source uncovered. The limited number of experiments was performed to gain an understanding of the shape of the thermal profile with no substrate reaction. The same inert substrate was used for comparison with the prior experiments.
>
> <u>Configuration 2a'</u>: Flat surface of a substrate consisting of two layers of the same blue denim fabric used in Section 5.2 over a slab of a FPUF. The fabric was from a different batch (from the same distributor) since the prior batch had been consumed. The FPUF was one of those examined in Reference 35. The candidate ignition sources were uncovered.
>
> <u>Configuration 3'</u>: Crevice of two blocks of the same FPUF as Configuration 2a', with each exposed surface covered with a single layer of the blue-striped fabric used in Section 5.2. Once again, the fabric was from a different batch (from the same distributor) since the prior batch had been consumed. The candidate ignition sources were covered with the UF-400 sheeting.

Each candidate, unless composed of reactive materials, was examined under at least two operating conditions, differing, e.g., in the initial temperature or the duration on the substrate.

The test results for the candidate sources were examined to gain insight into five questions:

1. For both igniting and non-igniting tests, what is the time-evolving temperature profile (local thermal condition) at the interface of a candidate ignition source and a test substrate?
2. To what extent is the potential for substrate ignition sensitive to the peak temperature and the duration of the elevated temperature of the ignition source?
3. Can a stationary ignition source lead to local thermal conditions and ignition propensity that are similar to those of a moving hot spot?
4. Can the local thermal conditions and cigarette ignition propensity be matched by a stationary hot spot that is *not* continuously heated?

5. To what extent does a chemical interaction between the ignition source and the substrate affect ignition propensity?

At this stage, it was not feasible to perform a sufficient number of tests to achieve a numerical match of the ignition fractions obtained with candidate ignition sources with those obtained using the SRM 1196 cigarettes. Rather, the ignition propensity comparison was based on coarse similarity of test results, e.g., between 5 % ignitions and 50 % ignitions (Low IP) or between 50 % ignitions and 90 % ignitions (High IP). (Comparing test results involving no ignitions or all ignitions was not informative, since it was unclear how far "off scale" such results were.) The metrics for comparing thermal performance involved the maximum thermocouple temperature between the potential ignition source and substrate, and the percentage of experiments that resulted in ignition.

The tests to determine the temperature profiles of the ignition sources on the inert substrate (Substrate 1) were performed in triplicate. Twelve replicates tests were performed for each of the ignition sources on the reactive substrates (Substrates 2a' and 3', respectively).

Each candidate source was assessed based on these results. Some candidates were not scheduled for additional testing, and the first experiments with some candidates resulted in not completing the planned test series. These might have required operating temperatures that were well beyond the range expected for a cigarette on an ignitable substrate; others might have been less promising than other candidates of the same type; still others might have showed ignition propensities that were too sensitive to small changes in operating temperature. There were also some candidates for which the early data looked promising and which were scheduled for additional testing.

Sections 6.2 through 6.4 describe the types of ignition sources and identify the selected representatives. Section 6.5 compiles and interprets the test results. In these Sections, and for the remainder of this Technical Note, Ignition Source 1 is the SRM 1196 cigarette.

6.2 Externally Powered Sources

6.2.1 Candidates

Cartridge heaters are readily available and were found to be useful for investigating the effect of differences in the characteristics of potential surrogate ignition sources. In particular, they made it easy to quickly study the effect of hot spot length and movement on the ignition propensity of a given substrate. It was recognized that practical considerations preclude the use of cartridge heaters for routine smoldering ignition standard testing. Each cartridge heater must be wired to a power source during a test. In tests such as in 16 CFR part 1632, in which 18 sources are required, the wiring would rapidly become unmanageable. Furthermore, it was found that the wiring made it difficult to properly orient the heater during a test. For example, the relative rigidity of the power wires made it difficult to lay the heaters flush with an upholstered foam fabric inside of a typical (draft-free) test enclosure.

A cartridge heater consists of electrical resistance wiring inside a cylindrical housing, with the power leads emanating from one end. Internally, the wiring coil extends to approximately 5 mm of either end of the housing. Thus, applying power results in a temperature distribution along the length of the cartridge, with the center being hotter than the ends. For a cartridge of high length-to-diameter ratio, there is likely to be a central region at a relatively uniform temperature, and the overall profile is roughly trapezoidal. For short, stubby cartridges, the temperature profile over the heater length is closer to triangular in shape. Since the housing material is an effective heat conductor, there is little variation in the temperature around a chosen circumference when the cartridge is suspended in air. However, when the cartridge is in contact with a substrate, this is not the case.

In this project, the effects of changes in multiple parameters were examined.

- Method of heating the cartridge,
- Length of the cartridge, and
- Whether the cartridge was stationary or moving.

In all cases, the electrically powered cartridge heaters were nominally 7 mm in diameter. The heaters were 27 mm long (similar to the length of the SRM 1196 coals on a reactive substrate) or 80 mm long (similar to the length of the SRM 1196 cigarette). Having data for two heated cartridge lengths offers an additional variable for replicating the performance of the SRM 1196 cigarette. In nearly all the experiments, the heater was placed in a 303 stainless steel sleeve 8 mm in outer diameter, the approximate diameter of a cigarette. The sleeve length for the 80 mm heater was 80 mm long.

In some of the tests with the short cartridge heaters, the heater was moved manually along the inside of the length of a sleeve. The sleeves for the stationary tests were 40 mm long; those for the moving tests were 80 mm long. Movement of the cartridge heater was intended to simulate the movement of the burning coal along the length of a cigarette. Since the tests were only intended to screen the candidate sources, the movements were done by hand at periodic intervals, resulting in an effective average rate of 0.04 mm/min. If behavior more exactly comparable to a burning cigarette were desired, the movement process should be automated.

Two heating modes were examined. In the first, the heater power was controlled so that the temperature at the heater/substrate interface was maintained to be constant. This would make it easier to compare the (single) interface temperature with that of the cigarette. In the second mode, the supplied power was kept constant. Since the linear burn rate and the effective heat of combustion are constant over most of the cigarette burn time, the constant power scenario is more representative of a typical cigarette. In both modes, the heater was turned on, allowed to reach the desired initial condition, and then placed on the substrate. The placement was such that the first thermocouple (TC6) was under the heater. Thus, for the shorter heated devices discussed later in this Technical Note, the device did not necessarily extend to the metal rim.

For operation of the heaters at constant temperature, at least 12 experiments with each source on each of the two reactive substrates were performed under at least two conditions. In the first set, the heater was powered to generate a peak heater/substrate interface temperature comparable to the peak value measured for the SRM 1196 cigarettes, T_{SRM}. In further sets, the temperature was raised or lowered in order to estimate the sensitivity of ignition to the heater temperature. The choice of the direction (higher, T^+, or lower, T^-) and the magnitude (50 ºC, 100 ºC, or 200 ºC) of the temperature change and the magnitude of the change depended on the fraction of the substrates ignited in the first set of 12 tests. The heater remained on the substrate at full temperature for at least 6 minutes.

For the constant power conditions, the initial power (P) and time (t) combination was selected as follows. We computed the area under the temperature/time curve for SRM 1196 cigarettes on Substrate 1(e.g., from Figure 8). We then performed preliminary experiments with each heater on the same substrate to determine the P and t values that gave a reasonable approximation to the cigarette curve shape and area.

The representative externally powered sources were:

2a: 27 mm long cartridge, placed in a 40 mm long stainless steel tube, constant peak temperature maintained by allowing the electric power to vary during a test.

2b: 27 mm long cartridge, placed in a 40 mm long stainless steel tube, constant electric power maintained during a test.

2c: 27 mm long cartridge, placed in an 80 mm long stainless steel tube, constant electric power maintained during a test; cartridge advanced manually at approximately 4 mm/min, corresponding to the 0.06 mm/s speed typical of the burning rate of the cigarettes on the reactive substrates (Table 2).

2d: 80 mm long cartridge, placed in an 80 mm long stainless steel tube, constant peak temperature maintained by allowing the electric power to vary during a test.

2e: 80 mm long cartridge, placed in an 80 mm long stainless steel tube, constant electric power maintained during a test.

6.2.2 Results

Figure 25 through Figure 29 show typical temperature distributions for each of the five ignition sources. Table 3 compiles the ignition frequency for each combination. The results for Source 2c, along with their relationship to the data for the SRM 1196 cigarette and the data for Source 2a, are discussed in Section 6.4.3 below.

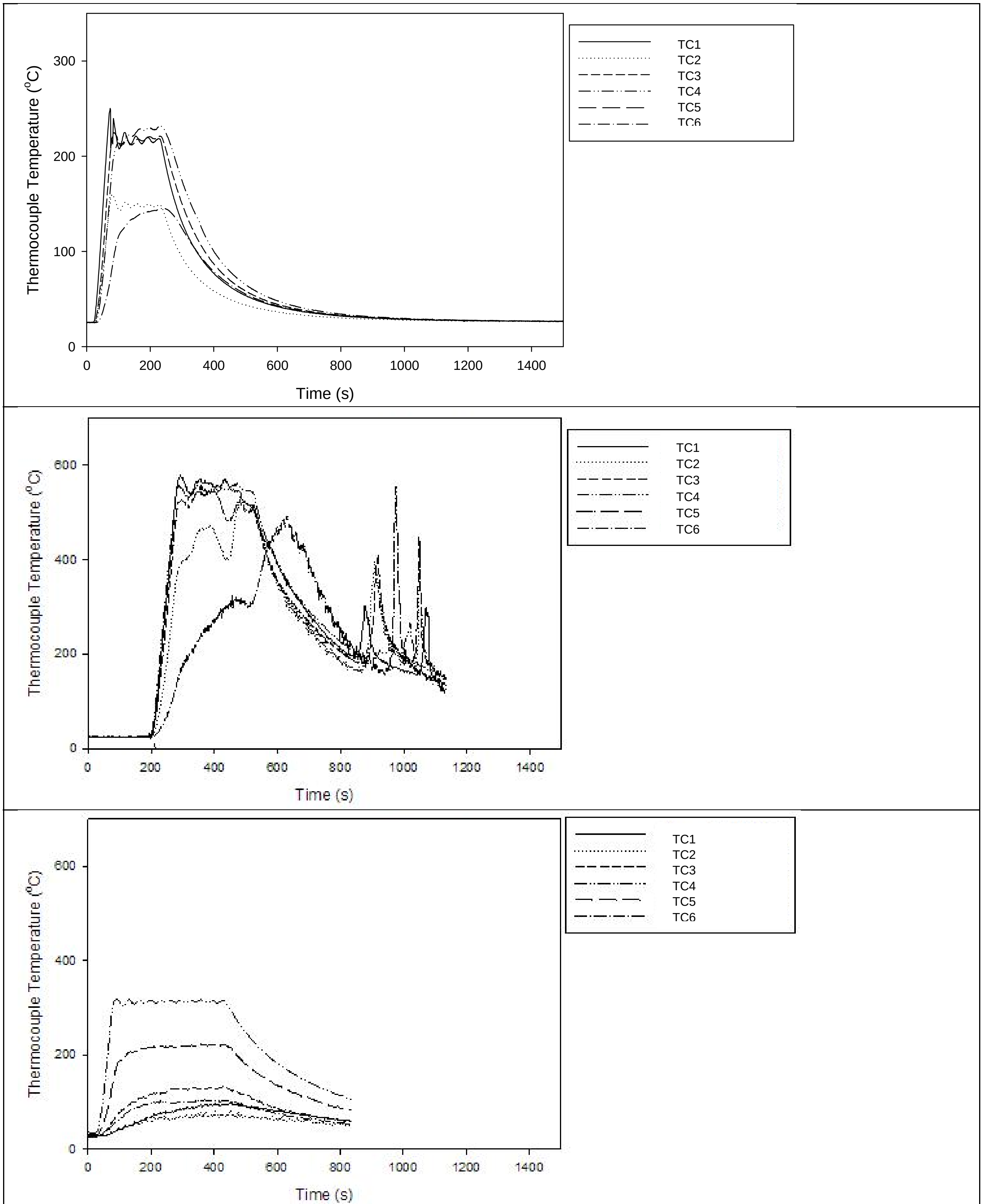


Figure 25. Temperature Measurements for Tests of a 27 mm Cartridge at Constant Temperature, in a 40 mm Stainless Steel Tube, on Three Substrates: top: inert; middle: flat; bottom: crevice.

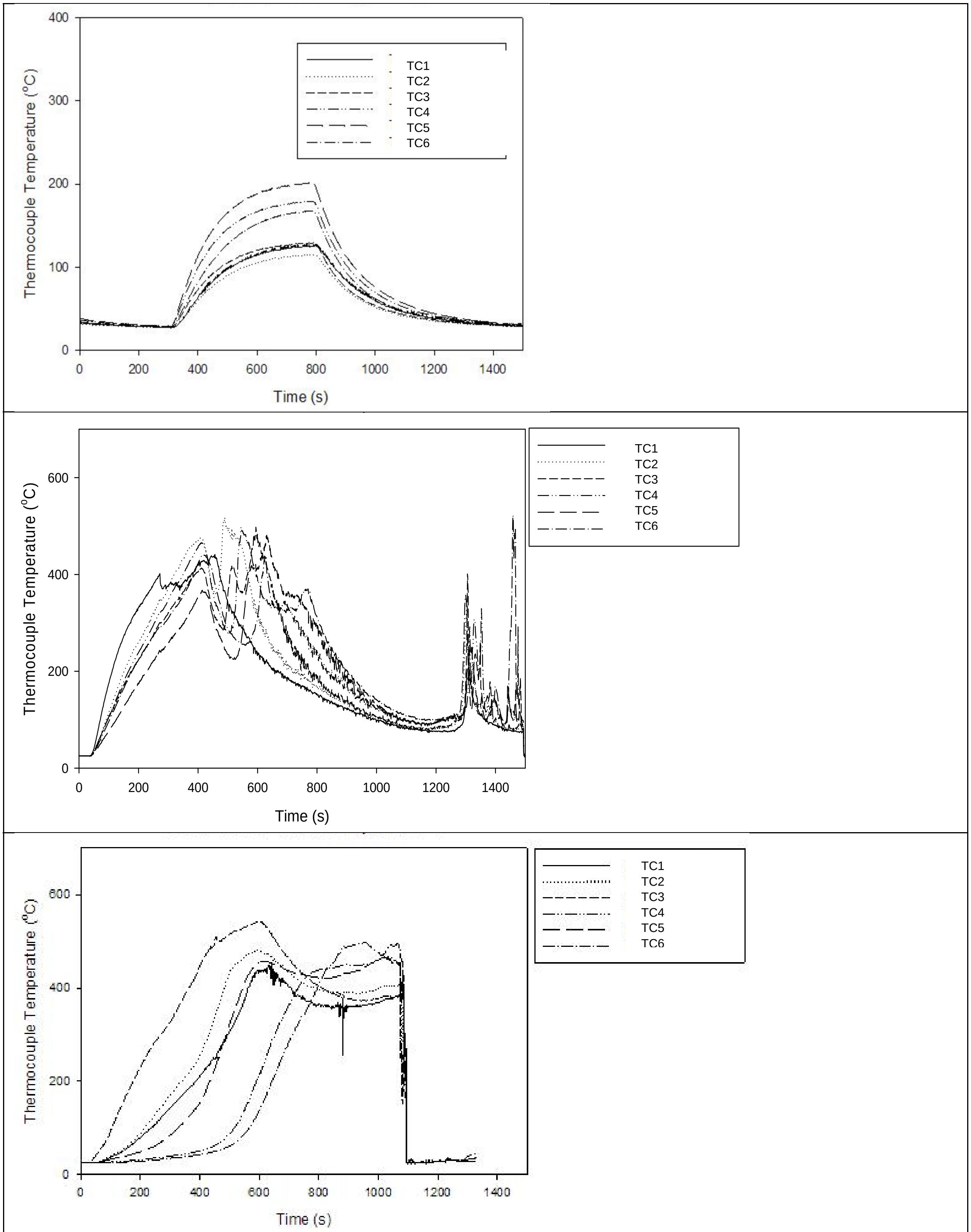


Figure 26. Temperature Measurements for Tests of a 27 mm Cartridge at Constant Power, in a 40 mm Stainless Steel Tube, on Three Substrates: top: inert; middle: flat; bottom: crevice.

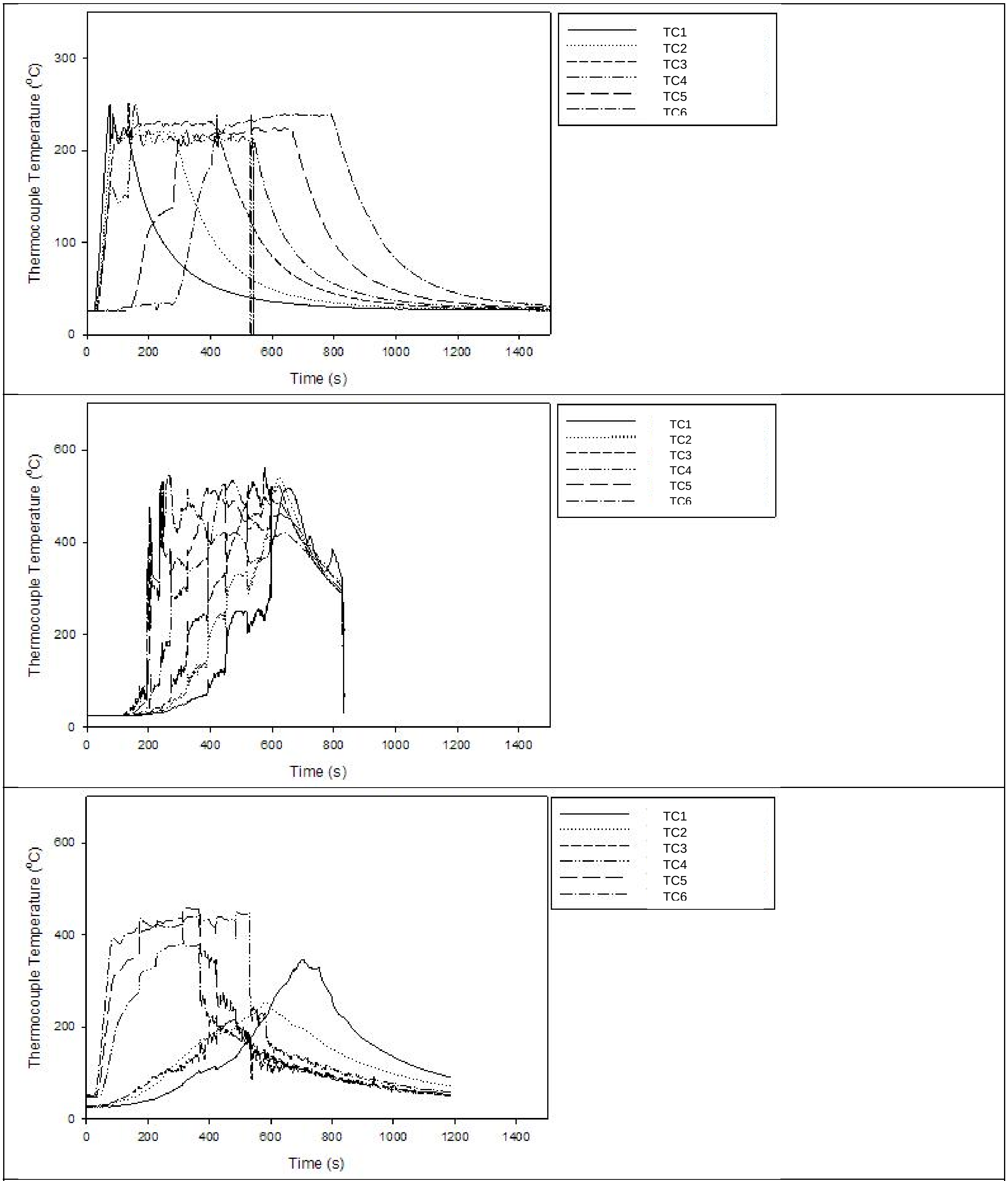


Figure 27. Temperature Measurements for Tests of a 27 mm Cartridge at Constant Power, Advanced within an 80 mm Stainless Steel Tube, on Three Substrates: top: inert; middle: flat; bottom: crevice.

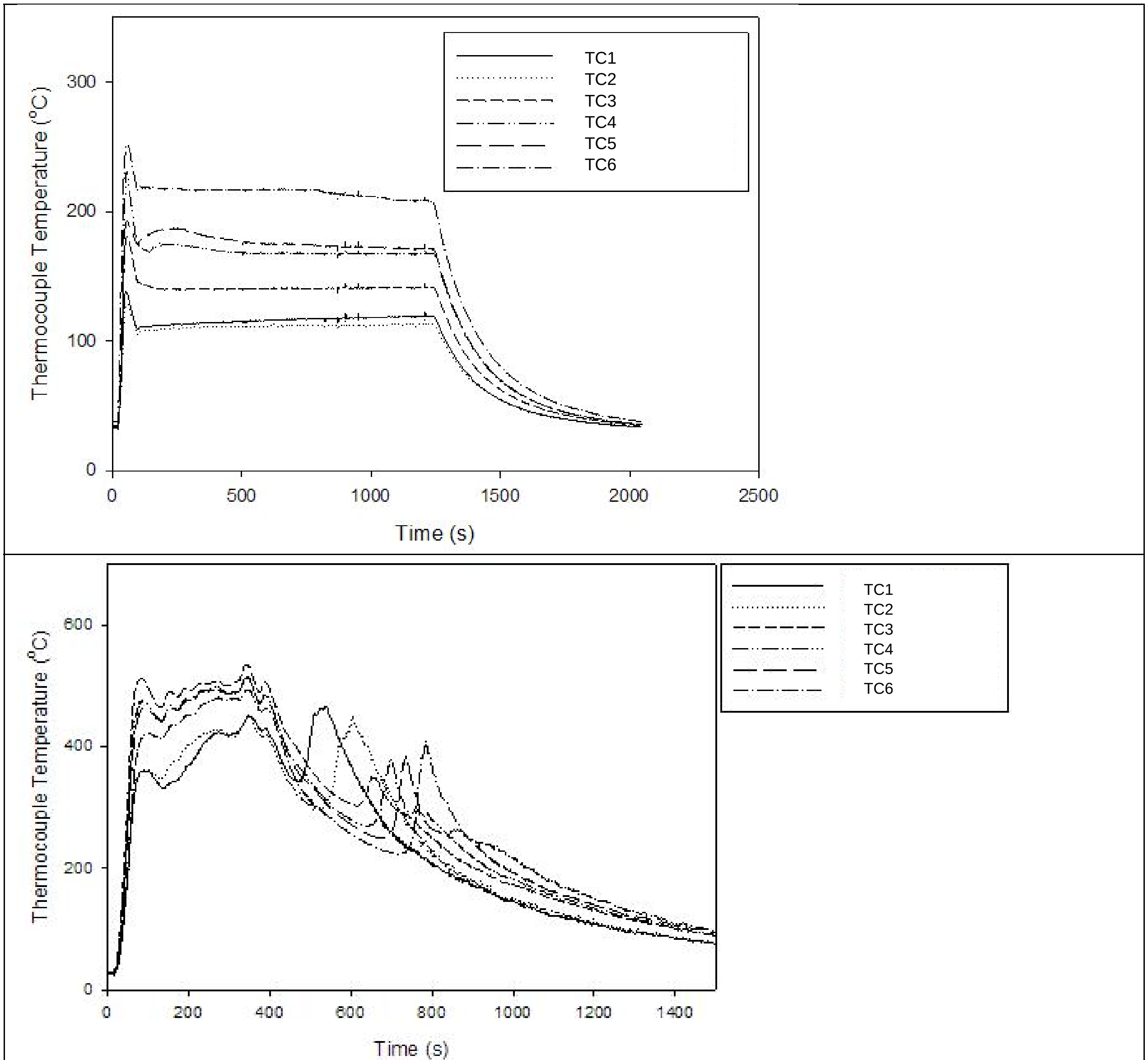


Figure 28. Temperature Measurements for Tests of an 80 mm Cartridge at Constant Temperature, in an 80 mm Stainless Steel Tube, on Two Substrates: top: inert; bottom: flat.

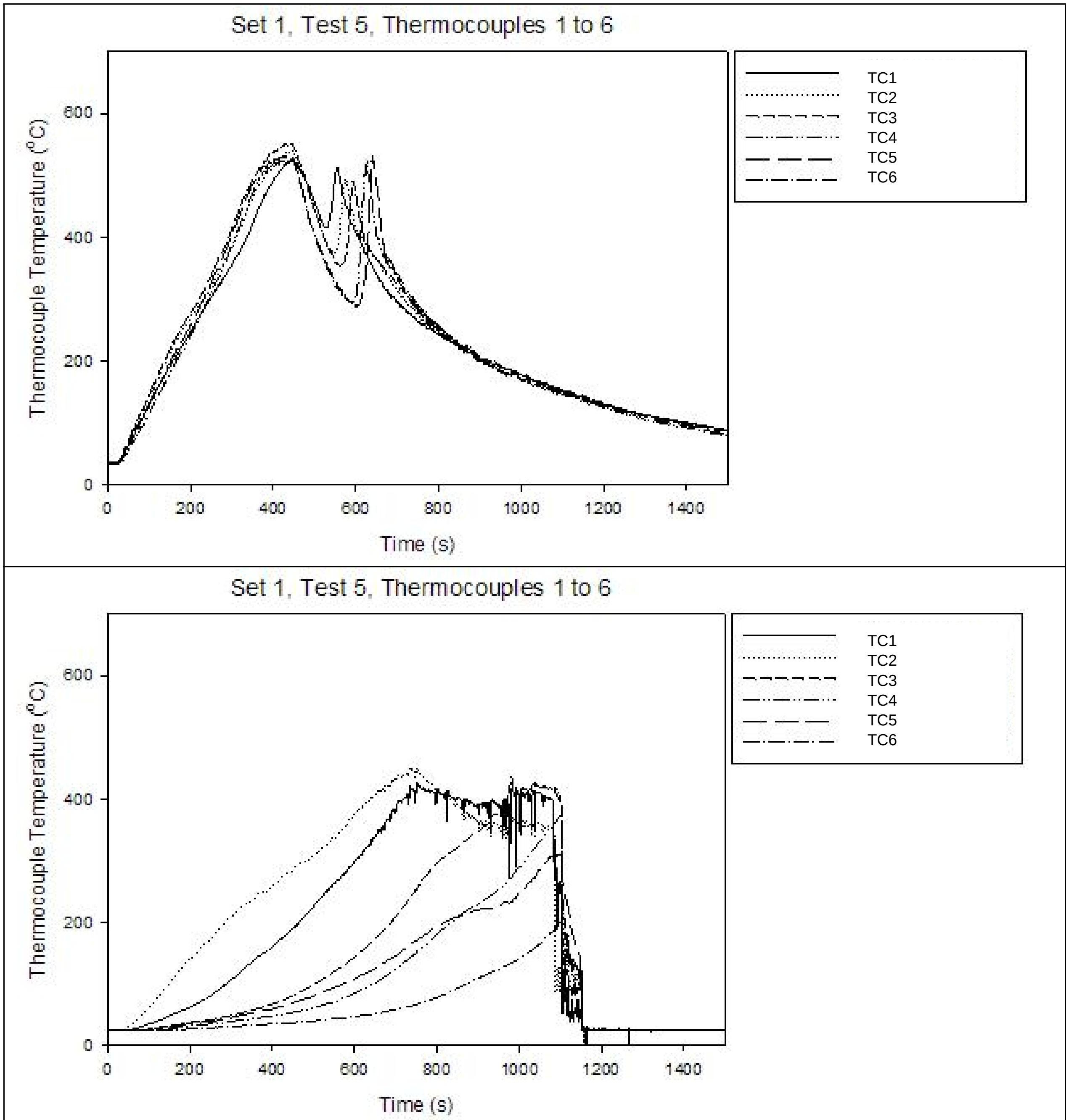


Figure 29. Temperature Measurements for Tests of an 80 mm Cartridge at Constant Power, in an 80 mm Stainless Steel Tube, on Two Substrates: top: flat; bottom: crevice.

The percentage of experiments resulting in ignition was compared to the ignition percentage for the SRM 1196 cigarettes. To the extent that they differed significantly, one or more additional sets of experiments were conducted with changes to the operating parameters of the cartridge heaters. These ensuing experiments were conducted without the thermocouple collar in place, since the critical observation was the magnitude and direction of any change in ignition propensity. The changes and the resulting ignition percentages are summarized in Table 3. Recall that, for this small number of replicate tests, the eventual ignition propensity comparison was based on Low IP (5 % to 50 % ignitions) or High IP (50 % to 90 % ignitions).

These results are specific to the particular cartridge heaters and the materials in the substrates. Nonetheless, they provide some guidance for further experiments:

- Sources for testing on the flat surface
    - The short ignition sources (2a and 2b) led to ignition at temperatures like those measured for the SRM 1196 cigarettes. These results are sensitive to the initial temperature, and precision to about ± 25 °C would be needed.
    - For ignition source 2c, an initial temperature of 475 °C is reasonable, but the act of advancing the heater through the tube was jerky and would require a precise mechanical translater.
    - The long ignition sources are promising: 2d at an initial temperature of 400 °C, and 2e at an initial power of a little less than 50 W. Note that the temperature for 2d is somewhat lower than the interface temperature for the SRM 1196 cigarette.
- Sources for testing in the crevice configuration
    - Sources 2a and 2c led to no ignitions, even at an initial temperature higher than that of the SRM 1196 cigarette.
    - The ignition percentage from source 2b was very sensitive to the time on the substrate.
    - Sources 2d and 2e approximated the ignition propensity of the SRM 1196 cigarettes.

6.3 Self-powered Sources

6.3.1 Battery Power

Battery-powered sources were considered for feasibility by addressing the question: How many batteries of the most viable type would be required to produce the same energy released by a typical cigarette? The average heat of combustion of tobacco was found by Sandusky [39] to be 17.36 kJ/g. The mass of an SRM 1196 cigarette is approximately 1.1 g. The total energy released by a burning cigarette is approximately 19 kJ.

Table 3. Ignition of Reactive Substrates by Cartridge Heaters.

Ignition Source		Substrate							
		Flat, uncovered				Crevice, covered			
		Ignition Source Change	Exps.	Igns.	%	Ignition Source Change	Exps.	Igns.	%
1	SRM 1196 (for comparison)	---	20	5	25	---	12	2	17
2a	27 mm cartridge in 40 mm SS tube, constant T (500 °C)	---	12	9	75	---	12	0	0
		Decrease T by 100 °C	12	0	0	Increase T by 100 °C	12	0	0
		Decrease T by 50 °C	12	0	0	---			
2b	27 mm cartridge in 40 mm SS tube, constant power (20 W, 6 min)	---	29	25	86	15 W, 7 min	6	4	67
		Decrease P by 4 W	4	0	0	Decrease t by 1 min	12	0	0
		Decrease P by 2 W	2	0	0	---			
2c	27 mm cartridge advanced in 80 mm SS tube, constant temperature (500 °C)	---	12	12	100	---	25	0	0
		Decrease T by 50 °C	12	6	50	Increase T by 100 °C	12	0	0
		Decrease T by 100 °C	12	1	8	---			
2d	80 mm cartridge in 80 mm SS tube, constant T (500 °C)	---	24	20	83	---	8	2	25
		Decrease T by 100 °C	28	15	54	---			
2e	80 mm cartridge, no sleeve, constant power (50 W)	---	18	9	50	26 W	10	3	30

The specific chemical energy of batteries is currently much smaller than that of hydrocarbon fuels. However, because of their relatively high energy density, zinc-air batteries have been widely implemented for small, lightweight devices such as hearing aids. For this reason, they could be considered as a power source for a surrogate smoldering ignition cartridge heater. The voltage of a zinc-air cell is 1.4 V. The highest capacity batteries currently available are around 620 mAh (or 2230 C). Therefore, the total available energy in a single zinc-air hearing aid battery is (1.4 V) × (2230 C) = 3.1 kJ. In order to produce the energy released by an SRM 1196 cigarette, it would be necessary to use about seven hearing aid batteries. This would result in a significant increase in the cost of a single test. The current cost of each battery is on the order of $0.30, to which is added the cost of the housing, etc. The current cost of an SRM 1196 cigarette is on the order of $0.70.

The currently commercial e-cigarettes use onboard batteries to heat the internal gas flow to a local temperature on the order of 100 °C. However, the temperature at the exterior of the cylinder (as well as that of the inhaled gas) is much lower, so that the user is not burned. In addition, the heater is typically on only during a puff, not continuously. For these reasons, considerable re-engineering would be needed for use as an SIS. Current battery capacity can be four times that of a zinc-air hearing aid battery, but costs about 20 times more.

There are additional concerns associated with using zinc-air batteries for smoldering ignition tests. First, zinc-air batteries require ambient oxygen, which might be significantly depleted as the substrate begins to smolder. Second, the maximum suggested operating temperature for hearing aid batteries is around 50 °C, whereas smoldering temperatures can reach up to 800 °C. The high temperature vulnerability could be mitigated by raising and insulating a battery from the heating element and substrate surface. However, a different type of battery would be needed to heat the substrate surface to ignition temperatures.

For these reasons, it is currently impractical to use the seven batteries required to generate the required energy to simulate the heat released by a single cigarette, and no tests were performed with battery-powered sources. Should future advances in battery technology lead to rechargeable cells with higher power density at lower cost, this approach could be reconsidered.

6.3.2 Chemically Reactive Sources

An alternative to electrochemical self-powered sources is the class of chemically self-powered sources—that is, sources that undergo exothermic chemical reactions. Several types of such sources were considered.

There are pairs of liquid that, when mixed, react exothermically. An example of such a reaction leading to a mildly elevated temperature can be found in some commercial hand warmers. However, to serve as an SIS, the reaction would need to reach temperatures on the order of 500 °C. Concern over both the safety of a two-component liquid system and the ability to achieve such a high temperature repeatably and without fracturing its containment ampule, led to discarding of this approach.

There are also solids that, once ignited, react exothermically. These include methenamine tablets, used to test carpeting for flaming ignition resistance, and “black snake” fireworks.

Custom formulations of the methenamine tablets would be needed for research to specify a formulation that would not be hot enough to ignite the substrate to flaming. The black snakes, typically a mixture of baking soda and sugar, burn unsteadily and tend to intumesce and curl, and are thus not conducive to repeatable tests. Incense (or punk) sticks were tested, but were found to burn at relatively unsteady rates and were insufficiently repeatable.

Charcoal is capable of smoldering and is commercially available in various forms. We obtained specimens of two types as the first set of representative chemically reactive sources:

> 3a: Pressed charcoal sticks used as the fuel in some hand warmers. The mass range for eight of the fuel sticks was (6.1 ± 0.7) g. The dimensions were (78 ± 5) mm long, (14.0 ± 0.9) mm wide, and (7.0 ± 0.6) mm thick.
>
> 3b: Willow charcoal sticks used for drawing. These came in nominally 3 mm, 5 mm, and 7 mm diameters. The lengths varied from about 20 mm to over 100 mm. A stick 20 mm long and 7 mm in diameter weighed 0.22 g. Figure 30 depicts specimens of both types of charcoal.

The sticks were all ignited using a small butane flame.

Figure 30. Photographs of two forms of charcoal: hand warmer fuel (left) and drawing sticks (right).

In preliminary experiments, the hand warmer sticks curled considerably and were therefore insufficiently repeatable to obtain consistent thermal interface temperatures. A series of eight experiments of the drawing sticks resulted in temperature profiles that were only somewhat more consistent (Figure 31). Even for these short sticks, the burning times (as indicated by the width of the TC temperature profiles) were more than double those of the SRM 1196 cigarettes.

Figure 32 shows that the mean peak temperature was approximately 225 °C, which is slightly hotter than the SRM 1196 cigarette on the same inert substrate. Because of the irregularities of the peak shapes, it was only possible to obtain indications of the linear burning rate for a fraction of the TC pairs. Figure 32 indicates that the preponderance of linear burning rates is between 0 mm/s (there is a peak at zero on the abscissa) and 0.03 mm/s. After an incubation period, the entire length of each of these sticks was smoldering, i.e., the coal length was 20 mm.

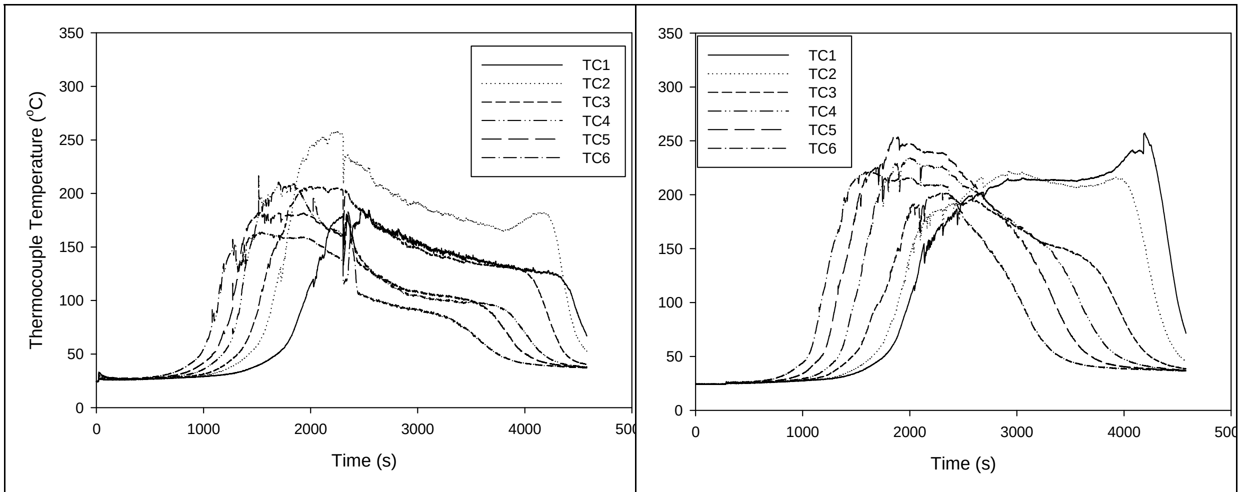


Figure 31. Temperature Measurements for Two Tests of Uncovered Willow Charcoal Drawing Sticks on an Inert Substrate.

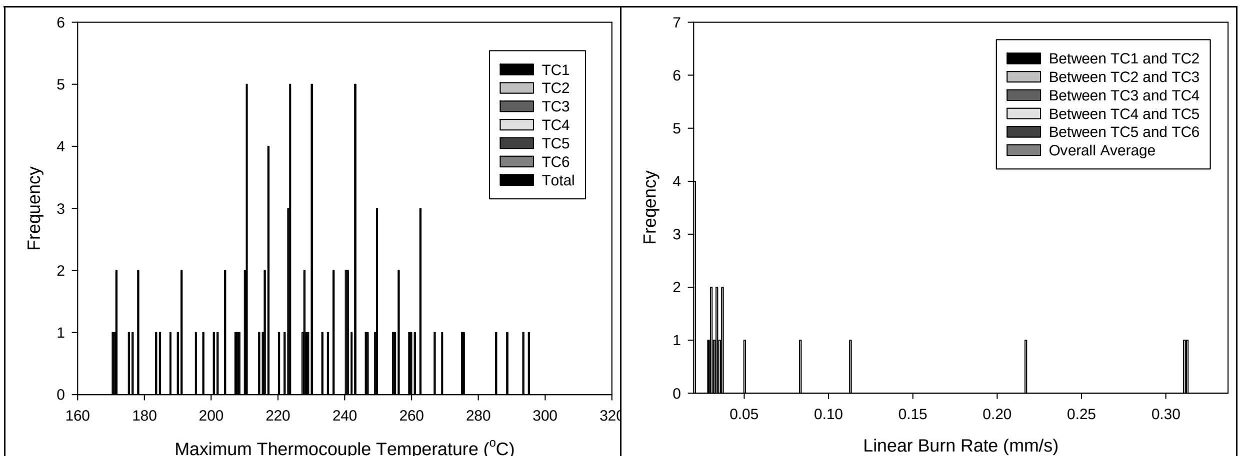


Figure 32. Distributions of Peak Temperature Measurements and Linear Burning Rates for Uncovered Willow Charcoal Drawing Sticks on an Inert Substrate.

We observed that, after an experiment, the center core of a willow charcoal drawing stick was consistently black while the surrounding charcoal residue was white. Inspection of unburned specimens found that each had a center core with a different physical appearance than the outer layer of softer charcoal. At the end of an experiment, this center core of each sample showed no signs of having undergone smoldering.

Cotton wool is also both capable of smoldering and commercially available in multiple forms. We obtained two such products: a pre-cut cotton rod with a flexible plastic shaft in the center, and continuous length gauze-wrapped surgical cotton wadding.

The first of these are called Parotis rolls and are used by dentists to keep a patient's mouth dry during a procedure. They are formed by wrapping a sheet of cotton wool tightly around a plastic spring. The material of the spring was not determined.

The second product consisted of layered sheets of cotton wool folded around a cotton cord. The cylinder is wrapped with a non-stick, latex-containing gauze. The roll was secured by gluing the gauze along the axial seam. Since the layers of cotton were folded and glued along the seam, instead of being wrapped around the central cord, the shape of the cross section was not consistently cylindrical, and the packing of the cotton material was much looser than the wound cotton rolls with a spring in the center. The packaging of the product as a continuous, 13.7 m long roll also contributed to cut pieces being slightly curved over their length and sometimes flattened through the cross-section. The most nearly cylindrical specimens were selected for the smoldering experiments. Some specimens were tested with the gauze layer removed.

Experiments were performed with four specimens of each type of cotton roll. Figure 33 shows photographs of some specimens. Table 4 contains the physical properties of the specimens. Figure 34 shows a temperature profile for Cotton Roll A, and Figure 35 shows the peak temperature and linear burn rate distributions. Figure 36 shows a temperature profile for Cotton Roll B, and Figure 37 show temperature profile for Cotton Roll C. All four specimens of Cotton Roll D extinguished before reaching any of the thermocouples.

Figure 33. Photographs of Cotton Rolls; top left: A; top right: B; bottom left and right: C.

Table 4. Physical Properties of the Tested Cotton Rolls.

Ignition Source		Description	Diameter (mm)	Length (mm)	Mean Mass and Standard Deviation (g)
3c	A	Parotis roll with plastic spring	9	80	1.4 ± 0.03
3d	B		8	100	1.5 ± 0.04
3e	C	Continuous gauze-wrapped cotton roll cut to length	≈ 8	80	0.9 ± 0.02
3f	D	Continuous gauze-wrapped cotton roll cut to length with gauze removed	≈ 8	80	0.7 ± 0.03

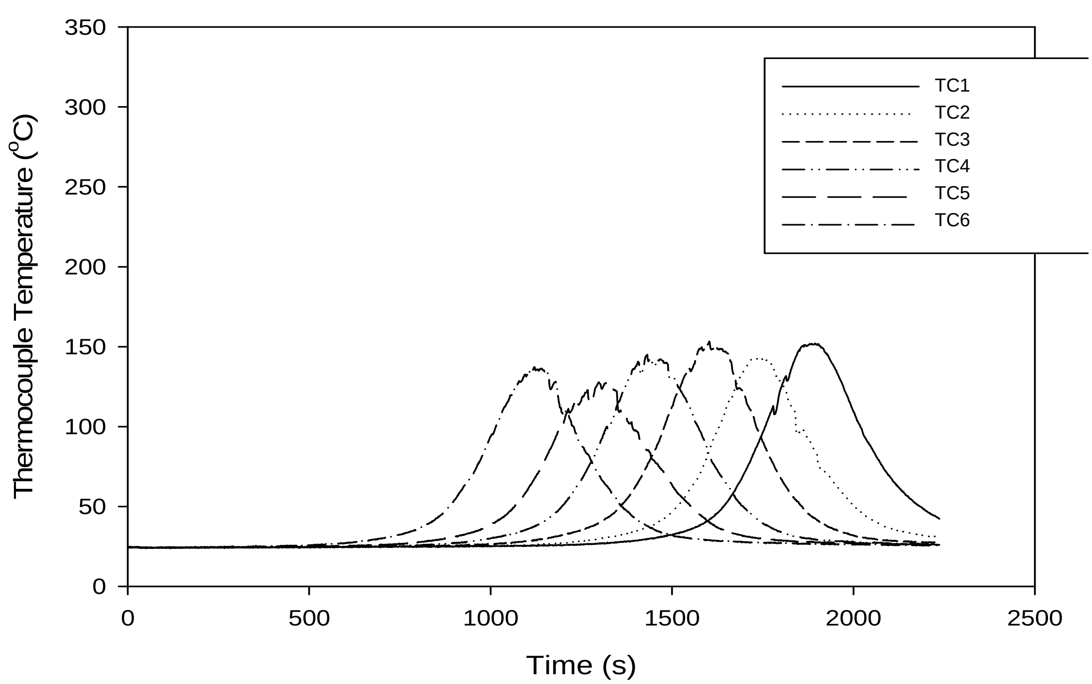


Figure 34. Temperature Measurements for an Uncovered 9 mm Parotis Roll on an Inert Substrate.

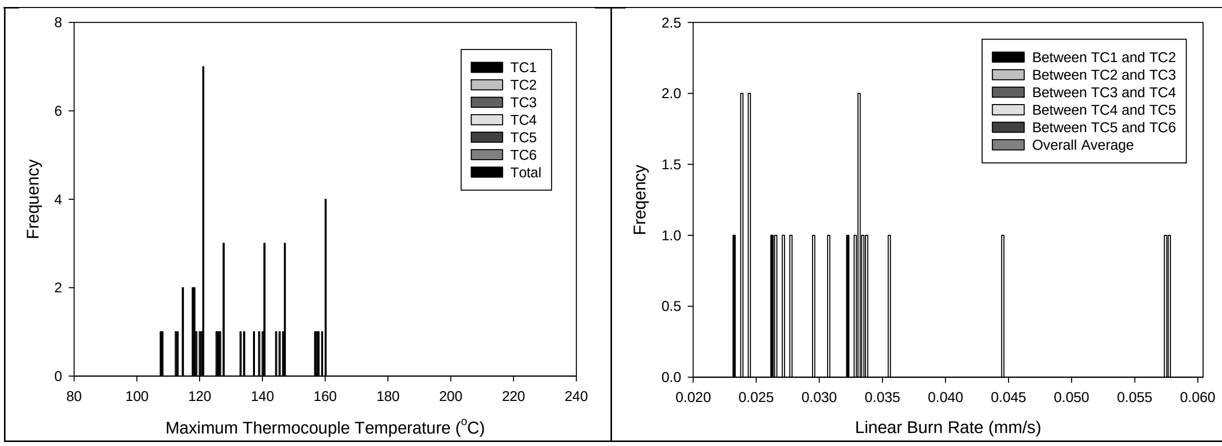


Figure 35. Distributions of Peak Temperature Measurements and Linear Burning Rates for Uncovered 9 mm Parotis Rolls on an Inert Substrate.

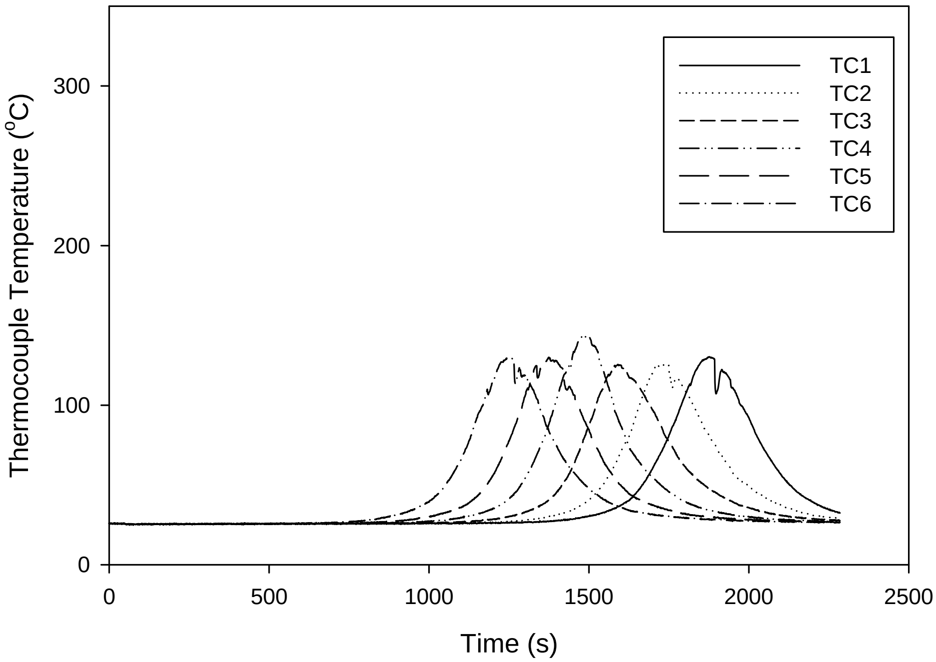


Figure 36. Temperature Measurements for an Uncovered 8 mm Parotis Roll on an Inert Substrate.

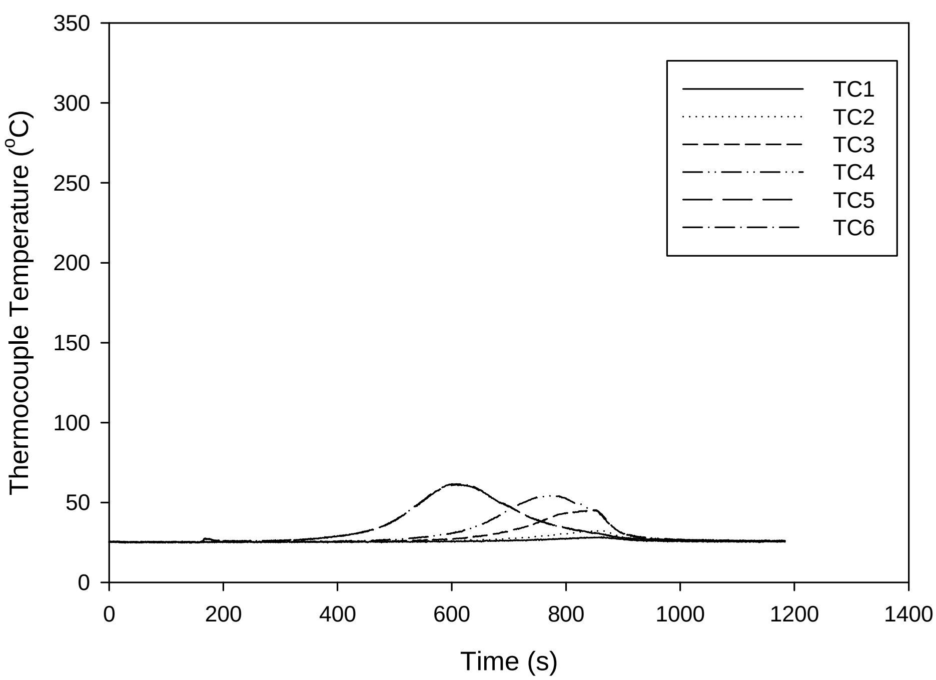


Figure 37. Temperature Measurements for an Uncovered, Gauze-wrapped 80 mm Cotton Roll on an Inert Substrate.

A diamond braided cotton rope had previously been examined by the CPSC staff, and then evaluated by six laboratories [40]. This rope was nominally 6 mm (0.25 in.) in diameter and was cut into 90 mm lengths, comparable to the lengths of commercial cigarettes. The core, several pieces of cotton yarn, was removed prior to testing. CPSC staff provided lengths of this rope for the current project. We also obtained a length of a solid, braided cotton rope of the same diameter. These were designated as the next two representative chemically reactive sources:

3g: Diamond braided cotton rope with the core removed, cut to 80 mm length.

3h. Solid, braided cotton rope (with no core that could be removed), cut to 80 mm length.

Both types of rope were examined uncovered on Substrates 1 and 2a' and covered on Substrate 3' (Section 6.1).

Four experiments were conducted on the inert substrate. Figure 38 shows a typical plot of the temperature profile from an experiment. The wide range of peak temperatures is a result of the rope distorting as it burns, affecting its contact with the successive TC beads. Figure 39 shows the peak temperatures from four of the experiments, demonstrating that this distortion was not unique to any specific thermocouple positions. The peak temperatures fell into two groups – one centered near 80 °C, the other centered near 280 °C. The linear burn rates were inconsistent, but centered near 0.02 mm/s.

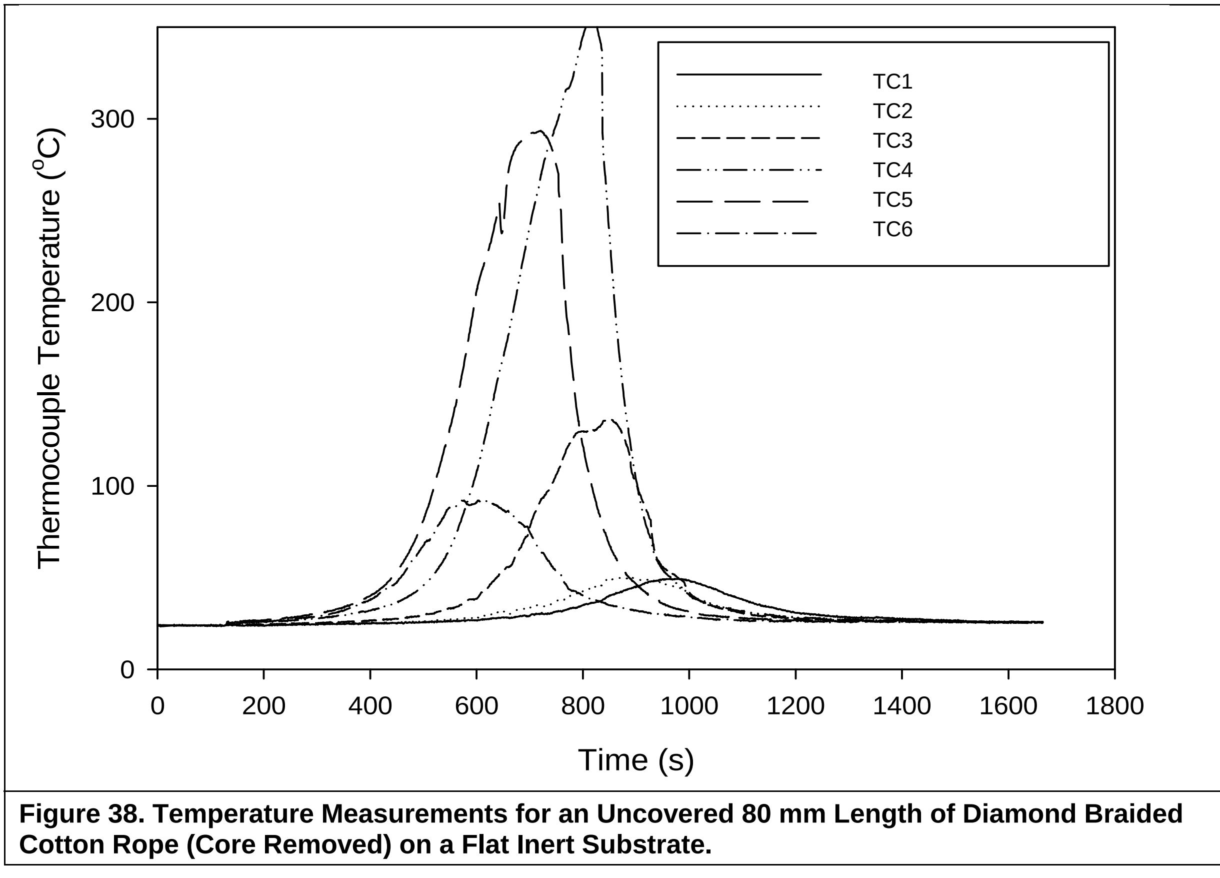


Figure 38. Temperature Measurements for an Uncovered 80 mm Length of Diamond Braided Cotton Rope (Core Removed) on a Flat Inert Substrate.

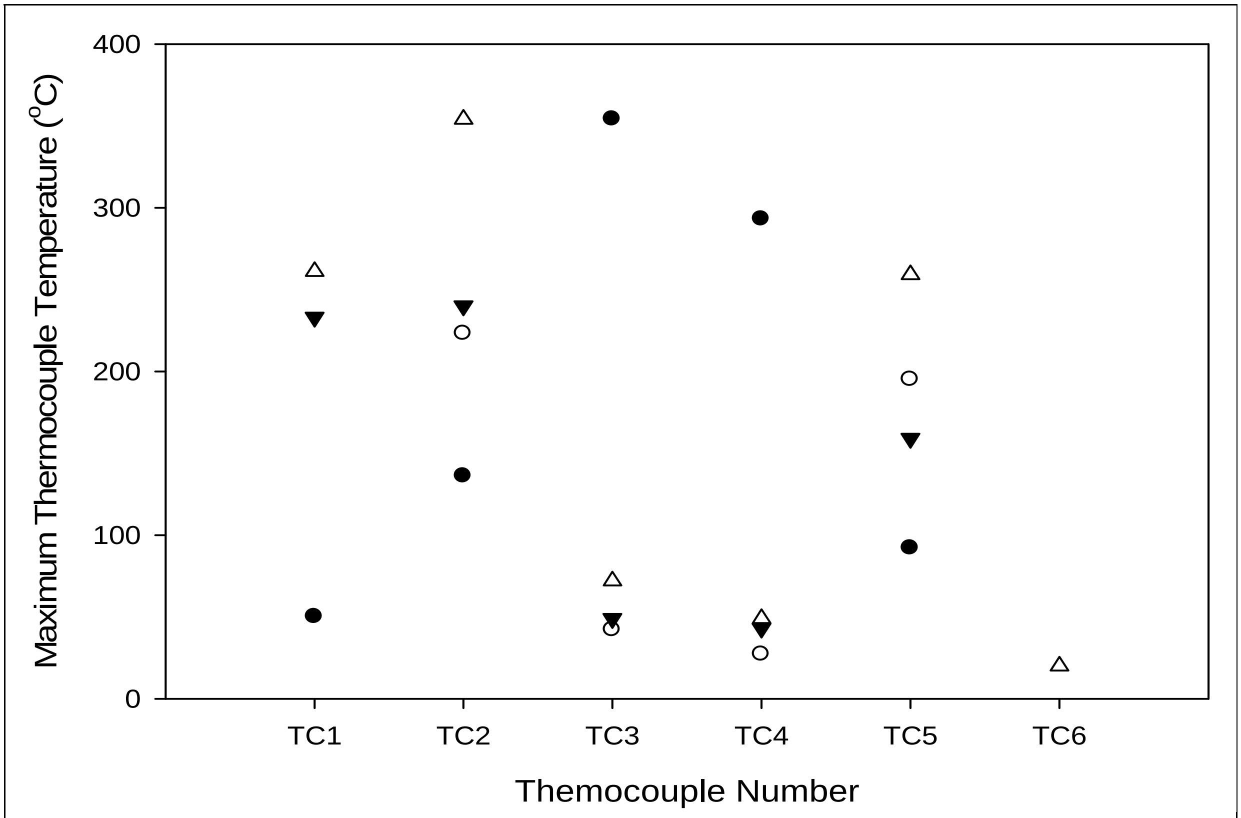


Figure 39. Peak Temperatures for Six Thermocouple Positions for Uncovered 80 mm Lengths of Diamond Braided Cotton Rope (Core Removed) on a Flat, Inert Substrate.

Twelve experiments with Source 3g on the flat reactive substrate resulted in five ignitions. Figure 40 shows the temperature profile form an experiment that resulted in an ignition.

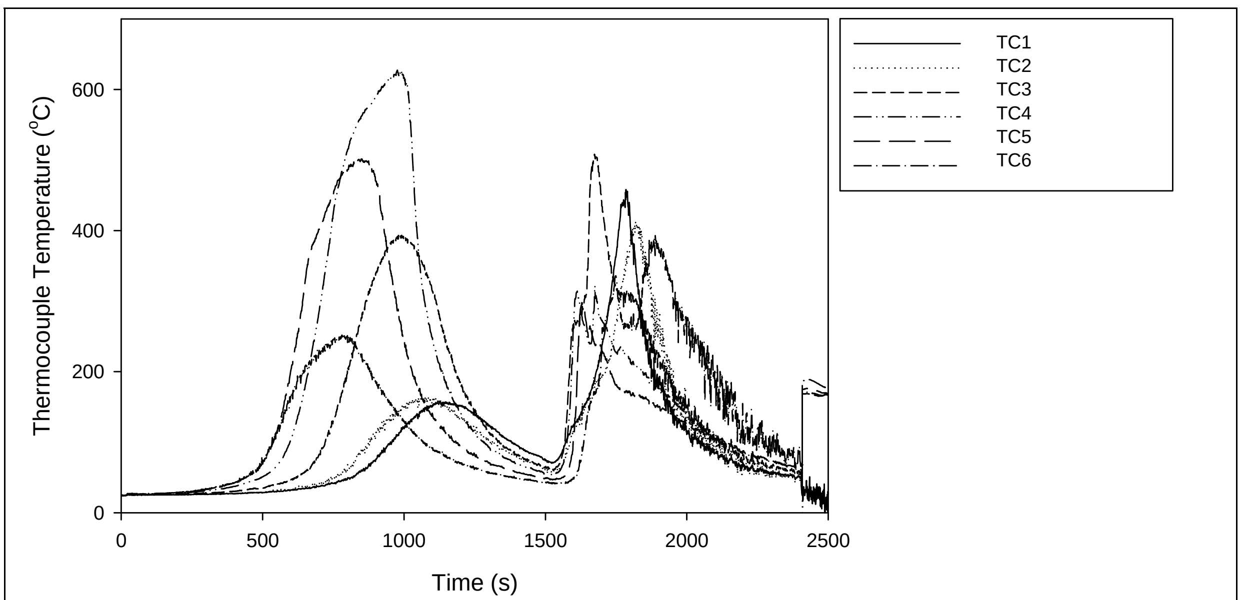


Figure 40. Temperature Measurements for an Uncovered 80 mm Length of Diamond Braided Cotton Rope (Core Removed) on a Flat, Reactive Substrate.

The mass of the rope specimens varied between 1.18 g and 1.32 g. Variation within this small mass range had no effect on the peak temperatures. The peak temperatures fell into two groups – one centered near 200 °C, the other centered near 550 °C. The linear burn rates were again inconsistent, but were near 0.06 mm/s.

Twelve experiments with Source 3g on the crevice substrate resulted in five ignitions. Figure 41 shows the temperature profile from an experiment that resulted in an ignition.

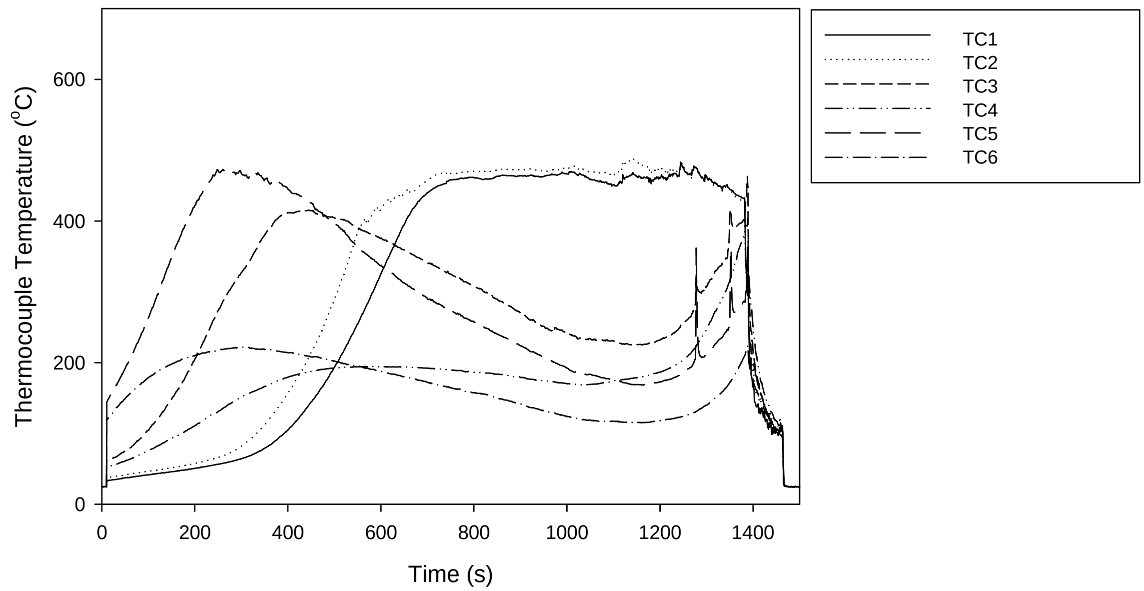


Figure 41. Temperature Measurements for a Covered 80 mm Length of Diamond Braided Cotton Rope (Core Removed) on a Crevice Reactive Substrate.

The mass of the rope specimens varied between 1.21 g and 1.32 g. The heaviest specimens were more likely to cause an ignition than the lightest specimens. The peak temperatures fell into two groups – one centered near 200 °C, the other centered near 450 °C. Once again, the linear burn rates varied considerably, with some clustering near 0.05 mm/s.

Four experiments with Source 3h were conducted on the inert substrate. Figure 42 shows a temperature profile from one of the experiments. Overall, the peak temperatures fell into two groups – one centered near 70 °C, the other centered near 240 °C. The linear burn rates were scattered, with an overall average near 0.02 mm/s.

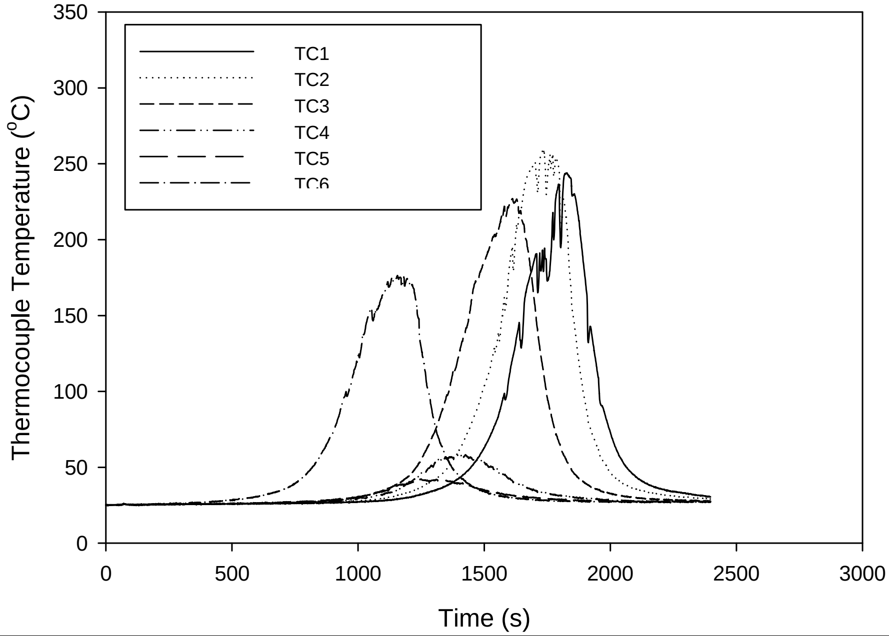


Figure 42. Temperature Measurements for an Uncovered 80 mm Length of Solid Core Diamond Braided Cotton Rope on a Flat Inert Substrate.

Twelve experiments with Source 3h on the flat reactive substrate resulted in two ignitions. Figure 40 shows the temperature profile form an experiment that resulted in an ignition. Overall, the peak temperatures fell into two groups – one centered near 150 °C, the other centered near 500 °C. The range of specimen mass was between 1.62 g and 1.74 g. The two ignitions occurred for specimens that were below the median mass. The linear burn rates were scattered, with an overall average near 0.03 mm/s.

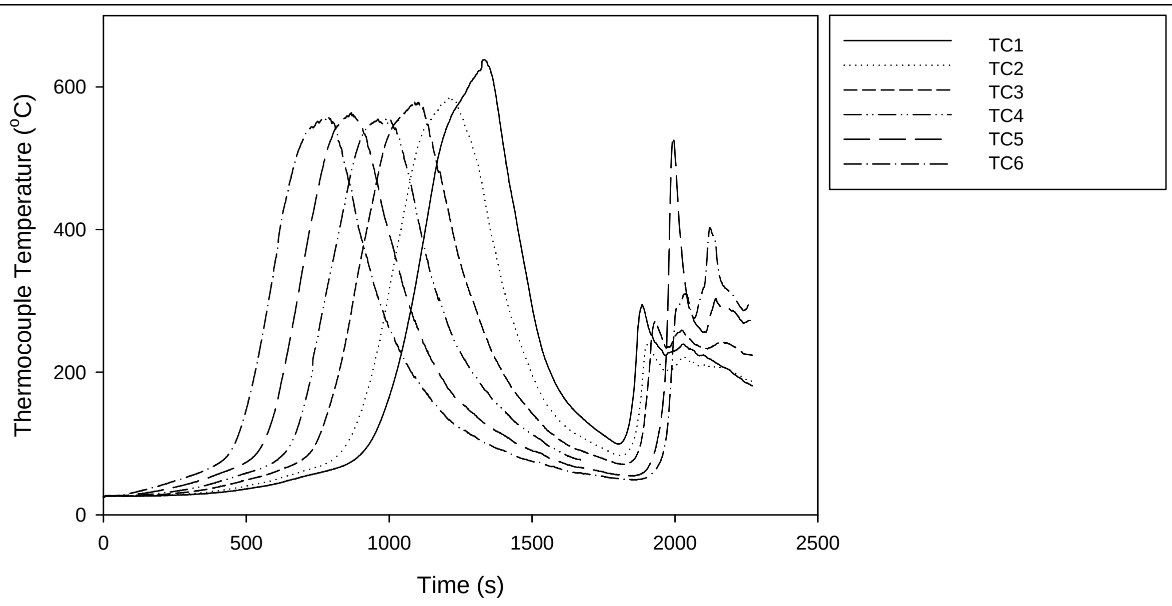


Figure 43. Temperature Measurements for an Uncovered 80 mm Length of Solid Core Diamond Braided Cotton Rope on a Flat Reactive Substrate.

Twelve experiments with Source 3h on the crevice substrate resulted in two ignitions. Figure 41 shows a temperature profile from an experiment that resulted in an ignition. Overall, the peak temperatures fell into two groups – one centered near 150 °C, the other centered near 420 °C. The range of specimen mass was between 1.64 g and 1.76 g. One ignition occurred with a low mass specimen, the other with a high mass specimen. The linear burn rates were scattered, with an overall average near 0.02 mm/s.

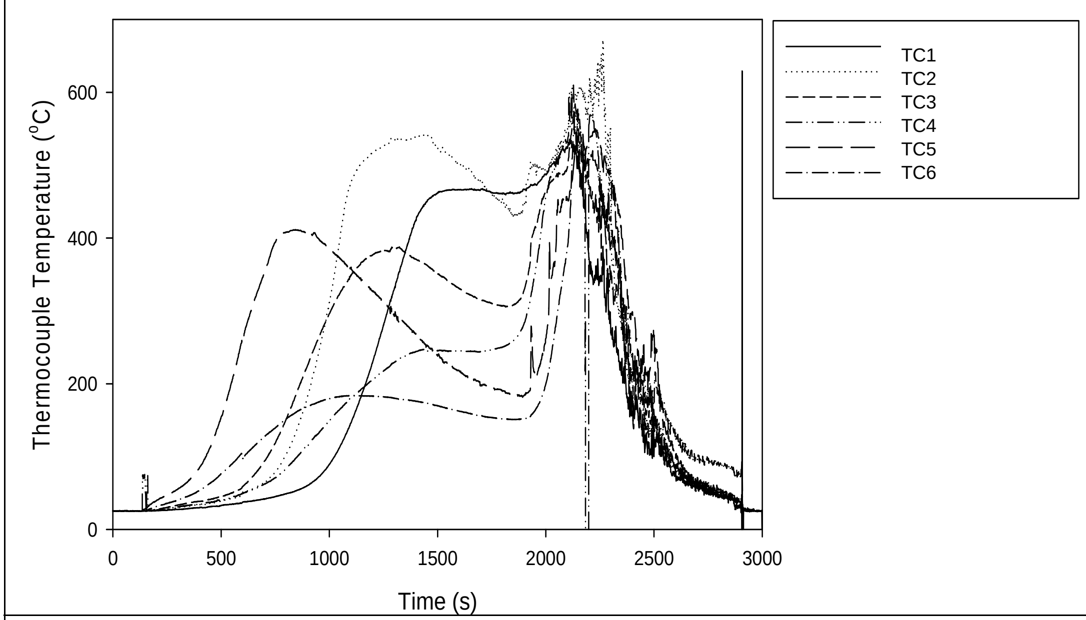


Figure 44. Temperature Measurements for a Covered 80 mm Length of Solid Core Diamond Braided Cotton Rope on a Crevice Reactive Substrate.

In all six combinations of source and configuration, the peak temperature *measurements* indicated significant movement of the rope relative to the thermocouple beads. The cluster of high temperatures is probably indicative of those that might lead to ignition, and these temperatures are consistent with the temperatures for the SRM 1196 cigarettes in both the flat and crevice configurations. Consistent with this, the ignition propensities of both ropes are similar to the ignition propensity of the SRM 1196 cigarettes on the same substrates.

However, cotton rope of this diameter is no longer a routinely manufactured item. It is currently only available by special order in a minimum spool size of 5000 ft. Since cotton is an agricultural product, it is expected that there will be variation amongst spools and even within spools. In particular, the ignition propensity data indicate the potential for a sensitivity to the mass of the test piece. A spool is composed of a series of spliced shorter lengths, each of which is subject to some degree of variation in mass. If cotton rope were to be considered further as a viable SIS candidate, a more comprehensive set of specifications is needed. This would require identifying which properties to specify, and developing methods so that testing labs can ensure uniformity within a batch and among many batches. The specification of rope properties should also be coupled to an expected variability in ignition propensity within the acceptable range of properties. Such a task would require characterizing and testing a large number of specimens.

Table 5 summarizes the results of experiments with reacting ignition sources.

Table 5. Behavior of Reacting Sources.

Ignition Source		Inert	Flat, uncovered			Crevice, covered			Notes
		Peak T (°C)	Igns./ Exps.	%	Peak T (°C)	Igns./ Exps.	%	Peak T (°C)	
1	SRM 1196 (for comparison)	190 °C ± 30 °C	5/20	25	570 °C ± 20 °C	2/12	17	430 °C ± 40 °C	
3a	Pressed charcoal sticks, 78 mm x 14 mm x 7 mm								Curled too much
3b	Willow charcoal sticks, 20 mm long x 7 mm diameter	225 °C ± 20 °C							Inhomogeneous composition
3c	Parotis roll with plastic spring, 80 mm long x 9 mm diameter	130 °C ± 10 °C							Not tested on reactive substrates – Peak T too low
3d	Parotis roll with plastic spring, 80 mm long x 8 mm diameter	120 °C ± 10 °C							Not tested on reactive substrates – Peak T too low
3e	Continuous gauze-wrapped cotton roll cut to length	*ca*. 40 °C							Not tested on reactive substrates – Peak T too low
3f	Continuous gauze-wrapped cotton roll cut to length with gauze removed								All specimens extinguished before reaching TCs
3g	Diamond braided cotton rope, core removed, 80 mm long x 6 mm diameter	*ca*. 280 °C	5/12	42	*ca*. 550 °C	5/12	42	*ca*. 450 °C	Mean temperatures of higher clusters
3h	Braided solid core cotton rope, core removed, 80 mm long x 6 mm diameter	*ca*. 240 °C	2/12	17	*ca*. 500 °C	2/12	17	*ca*. 420 °C	Mean temperatures of higher clusters

Since the easiest tests to perform were those on the inert substrate, an early criterion for evaluating these ignition sources was the peak temperatures relative to the peak temperatures for the SRM 1196 cigarettes. None of the four types of cotton rolls approached the 190 °C value for the cigarettes, so it was unlikely that any of these would have been able to ignite the reactive substrates.

The two ropes behaved much as the diamond braided rope did in the CPSC research. The higher clusters of peak temperatures represented those instances where there was better contact with the TC beads, and these values on both inert and reactive substrates were comparable to the equivalent temperatures for the SRM cigarettes. The ignition percentages were also consistent. The linear burn rate for the diamond braided rope on the flat reactive substrate was consistent with that for the cigarettes; on the crevice the rope linear burn rate was faster than the cigarette's. The linear burn rate for the solid core rope on the flat reactive substrate was substantially lower than that for the cigarettes; on the crevice, the rope linear burn rate was comparable to the cigarette's burn rate. There was an observed variability in the mass for a small number of outlier samples of the ropes due to the presence of splices. A mass specification would avoid these specimens introducing scatter into test results. The ropes might have merited further examination, had it not been for their cloudy future availability.

The shapes of the charcoal drawing sticks appeared somewhat irregular, and these particular sticks appeared to be inhomogeneous in composition. There was a cluster of estimated linear burning rate values that were significantly slower than those for the SRM cigarettes. There were also unpredictable instances of acceleration to burn rates similar to those for the cigarettes. For these reasons, these charcoal drawing sticks were not examined further.

6.4 Preheated Sources

6.4.1 Pre-set Cartridge Heaters

The third type of ignition source comprises pieces of materials (also referred to as "slugs") that are heated to a selected temperature. An advantage of this category of candidates is that, by varying the composition and dimensions of the slug, one could obtain a near continuum of thermal behavior. A limitation is that, once the slug is on the substrate, it will cool continuously. This means that the ignition performance might not be characterized by a unique temperature, and comparison with the interface temperature profiles generated by an SRM 1196 cigarette might be difficult.

To start looking at this type of candidates, we examined two sizes of cartridge heaters as representative preheated sources:

4a: 27 mm cartridge heater in a 40 mm sleeve.

4b. 80 mm cartridge heater in an 80 mm sleeve.

In an experiment, the heater was placed on the substrate and the power was applied until the temperature approximated the desired value. The power was then turned off, and the heater remained unpowered on the substrate for at least 10 min. For both sources, The initial temperatures were 300 °C on the inert substrate, and 600 °C on the two reactive substrates.

Subsequent experiments with the initial temperature varied enabled obtaining ignition fractions similar to those obtained with the SRM 1196 cigarettes.

Table 6 compiles the percentages of ignitions that occurred for experiments with these two candidate sources on the two reactive substrates. Figure 45 and Figure 46 show thermal profiles of the interface temperatures.

Recalling that the SRM 1196 cigarettes ignited this flat substrate in 25 % of the experiments, it appears that an initial temperature of approximately 450 °C would produce a comparable result for both heaters. The interface temperature for the cigarettes was approximately 100 °C higher. The much lower ignition percentage for the heater at 700 °C reflects a phenomenon different from a cigarette. The heavy heater burned through the fabric, melted the foam, and fell into the created cavity, collapsing the pore structure of the foam. Thus, there were few smoldering ignitions. These two temperature-based observations suggest that the ignition performance of this type of heater might well vary significantly when testing different fabrics and padding materials.

For the crevice configuration, we observed no ignitions with the shorter heater, up to the point where it fell into the substrate. With the longer heater, the ignition percentage was comparable to that for the SRM 1196 cigarettes, but the initial temperature was well over 100 °C higher than the peak cigarette-substrate interface temperature.

Table 6. Outcomes of Pre-set Cartridge Heaters on Reactive Substrates.

Heater	$T_{initial}$ (°C)	Substrate			
		Flat, uncovered		Crevice, covered	
		Igns./Exps.	% Ignitions	Igns./Exps.	% Ignitions
27 mm heater in 40 mm stainless steel sleeve	400 °C	0/12	0	---	---
	450 °C	---	---	0/20	0
	500 °C	21/24	88	0/25	0
	600 °C	---	---	0/12	0
	700 °C	2/24	8	---	---
80 mm heater in in 80 mm stainless steel sleeve	450 °C	10/24	42	---	---
	500 °C	20/24	83	---	---
	600 °C	---	---	3/10	30

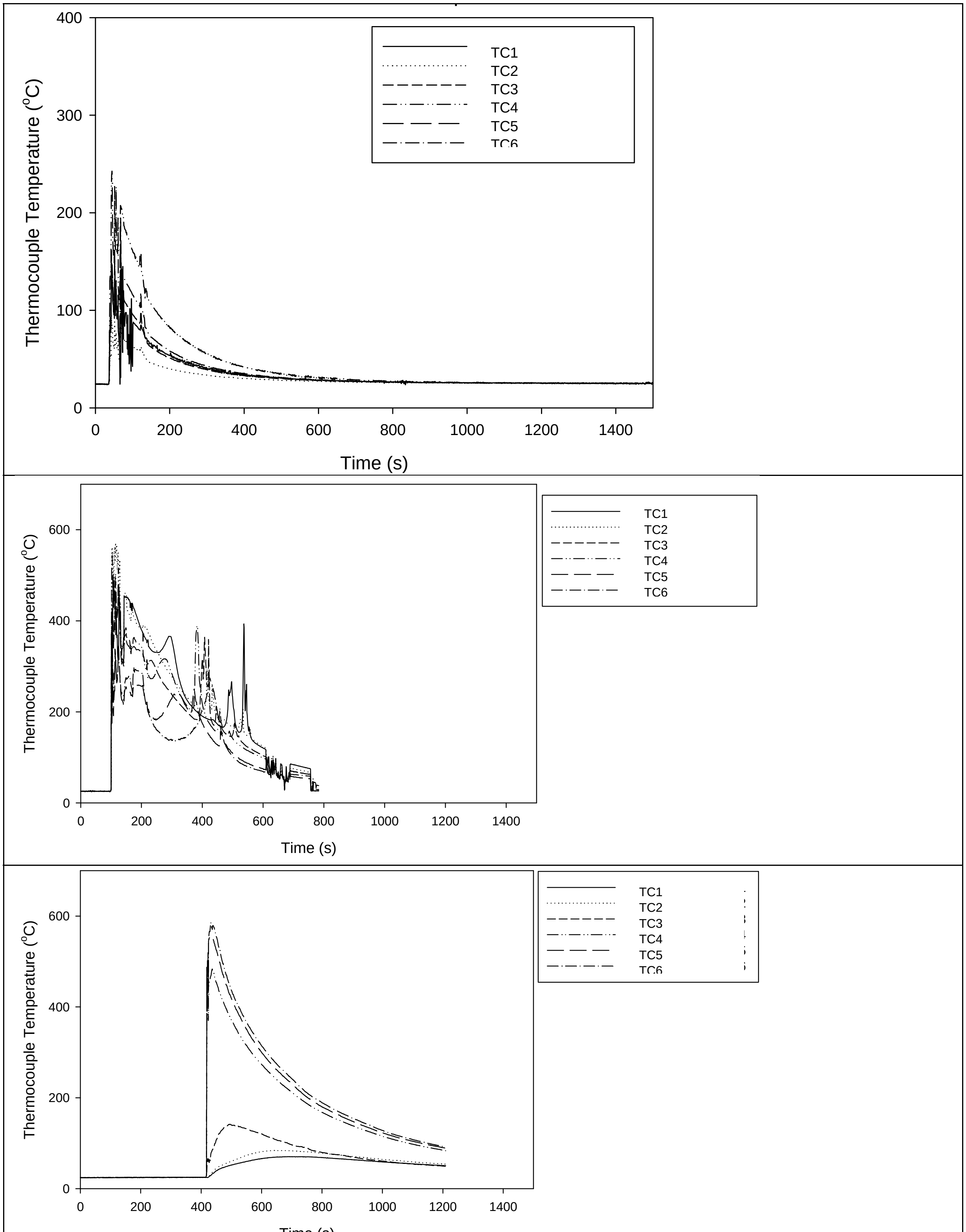


Figure 45. Temperature Measurements for Tests of a Preheated 27 mm Cartridge in a 40 mm Stainless Steel Tube on Three Substrates: top: inert (ca. 300 °C); middle: flat (ca. 600 °C); bottom: crevice (ca. 600 °C).

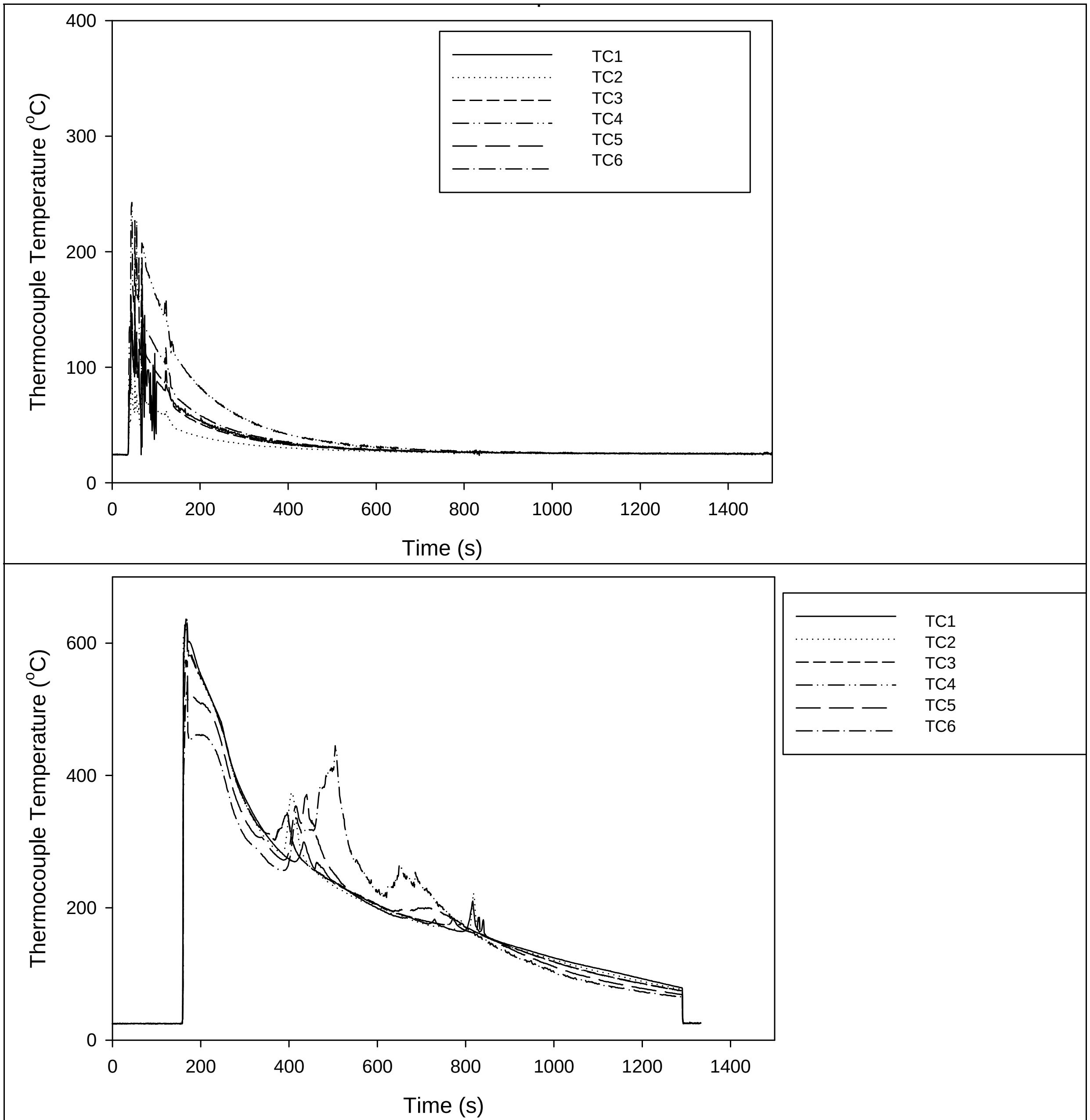


Figure 46. Temperature Measurements for Tests of a Preheated 80 mm Cartridge Heater in an 80 mm Stainless Steel Tube on Two Substrates: top: inert (ca. 300 °C); middle: flat (ca. 700 °C).

6.4.2 Slugs

The results of the exploratory experiments with cartridge heaters suggested that it might be possible to identify a preheated ignition source that (a) manifests a similar ignition propensity to the SRM 1196 cigarette on these substrates and (b) does so under thermal conditions similar to those generated by the coal of a cigarette. It would also be necessary that such an ignition source be free of the electrical leads that make routine testing difficult.

We investigated this concept by heating slugs in an oven. The heated slugs were removed and quickly placed on the two reactive substrates. Replicate experiments led to estimates of the frequency with which ignition resulted.

The slugs could be made of differing materials (with differing physical and thermal properties) and have different dimensions and shapes. By independently varying these parameters, it is, in theory, possible to find slugs that approximate the ignition performance of the SRM 1196 cigarette. One constraint was that the slugs not melt or otherwise deform during the course of an experiment, i.e., the slug must be stable at temperatures near 600 °C. Another constrain was that the slug not be so massive as to collapse the thermally degrading substrate.

Table 7 lists the properties of three readily available materials we used to explore the potential of this kind of candidate ignition source. They possess a range of values of mass and of thermal inertia (the product of the thermal conductivity, density, and heat capacity). They are all physically stable above the highest measured cigarette-substrate interface temperatures.

Table 7. Thermophysical Properties of Tested Slugs.

Material	Thermal Conductivity (W/m·K)	Density (g/cm^3)	Heat Capacity (J/g·K)	Mass (20 mm length) (g)
303 stainless steel rod, 8 mm diameter	16 (100 °C)	8.0	0.50	7.7
303 stainless steel tube, 8 mm outer diameter and 7.2 mm inner diameter	16 (100 °C)	8.0	0.50	1.5
Brass rod, 8 mm diameter	115 (20 °C)	8.5	0.38	5.8
Alumina rod, 8 mm diameter	30	3.9	0.78	3.8

To match the geometry of conventional test cigarettes, we prepared cylindrical slugs 8 mm in diameter for all four materials. We used three lengths: 20 mm (which was in the length range of the hottest part of the cigarette coal), 40 mm (which was in the total length range of the cigarette coal), and 80 mm. Figure 47 and Figure 48 are photographs of the stainless steel rods and tubes. 10 mm long rods and tubes are shown, but were not tested, based on the results for the other lengths, as discussed below.

Early concerns were the magnitude and rate of the slug's temperature drop during its transfer from the oven to the substrate surface. The *magnitude* would affect the choice of oven temperature that would result in the desired slug temperature at the time of its deposit on the substrate. The *cooling rate* must be sufficiently low that it is not a significant source of uncertainty in the ignition propensity.

This cooling was modeled, and the accuracy of the model was verified by subsequent experimentation. In the model, the slug began at an elevated, uniform temperature and lost heat by buoyancy-induced convection and by radiation. Heat transfer within the slug was assumed to be faster than heat loss to the surroundings, so there was no temperature gradient within the slug. The convective heat transfer coefficient correlation was taken from Mills [41] for flow over a horizontal cylinder. The thermophysical properties were taken from tables in Reference 41. The resultant temperature profiles for 80 mm long brass and alumina slugs with initial temperatures of 600 °C are plotted in Figure 49.

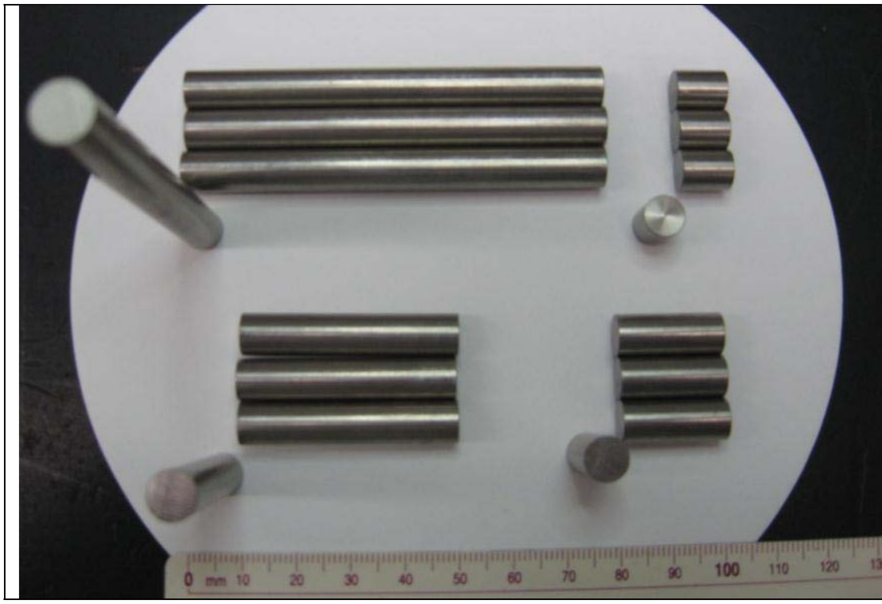


Figure 47. Photograph of the 303 Stainless Steel Rods.

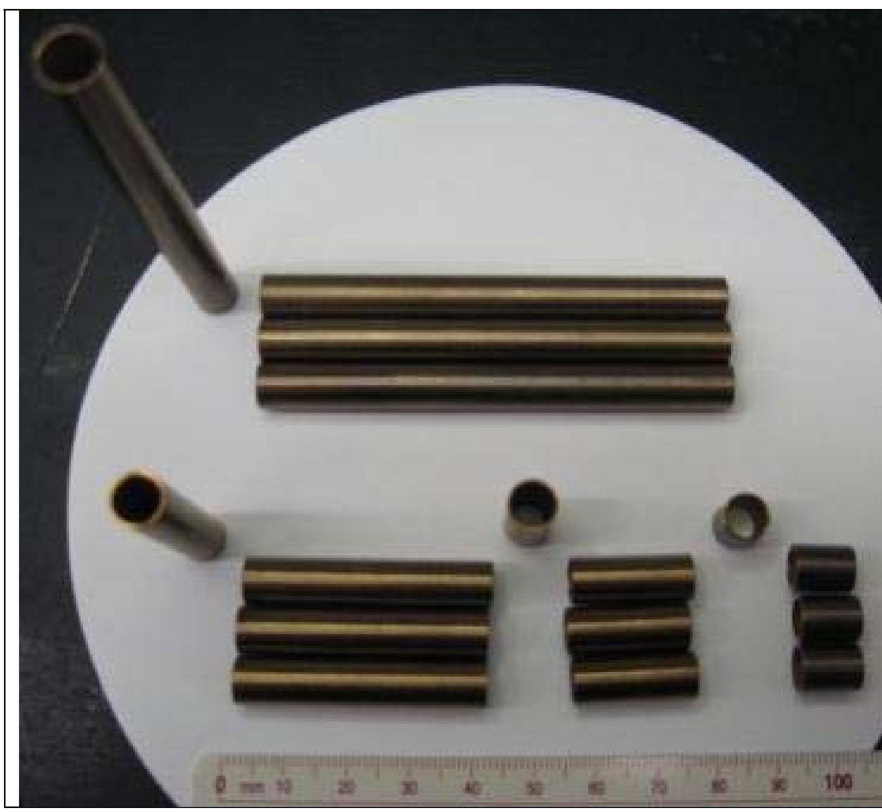


Figure 48. Photograph of the 303 Stainless Steel Tubes.

To obtain the experimental data, a slug was removed from the oven with metal tongs and quickly placed directly on top of a thermocouple array, which was supported on its sides by several layers of filter paper, as shown in Figure 50. The interface temperature profiles are also plotted in Figure 49.

The model agrees with the experimental data quite well. At 1 min, the model and experiment differed by approximately 30 °C for both slugs. At 5 min, this had grown to a 50 °C difference for the brass slug and shrunk to essentially zero for the alumina slug. These discrepancies are likely due to slight differences between the actual thermophysical properties and the tabulated values that were assumed in the model.

Figure 49 shows that the temperature decay is fairly rapid, implying that the heating of the substrate could be fairly sensitive to operator behavior and laboratory setup. Fortunately, we found that, for a typical operator, the time needed to move the slug from the oven to the substrate was about 10 s ± 3 s. This translates to an uncertainty in the initial slug temperature on the substrate of less than ± 10 °C, certainly a tolerable value. This could vary in different laboratories, so a formal operating procedure would be needed to assure this small magnitude. The transfer time could also be kept small by replacing the oven with an insulated heating block with wells for the slugs. Such a block could be located close to the substrate.

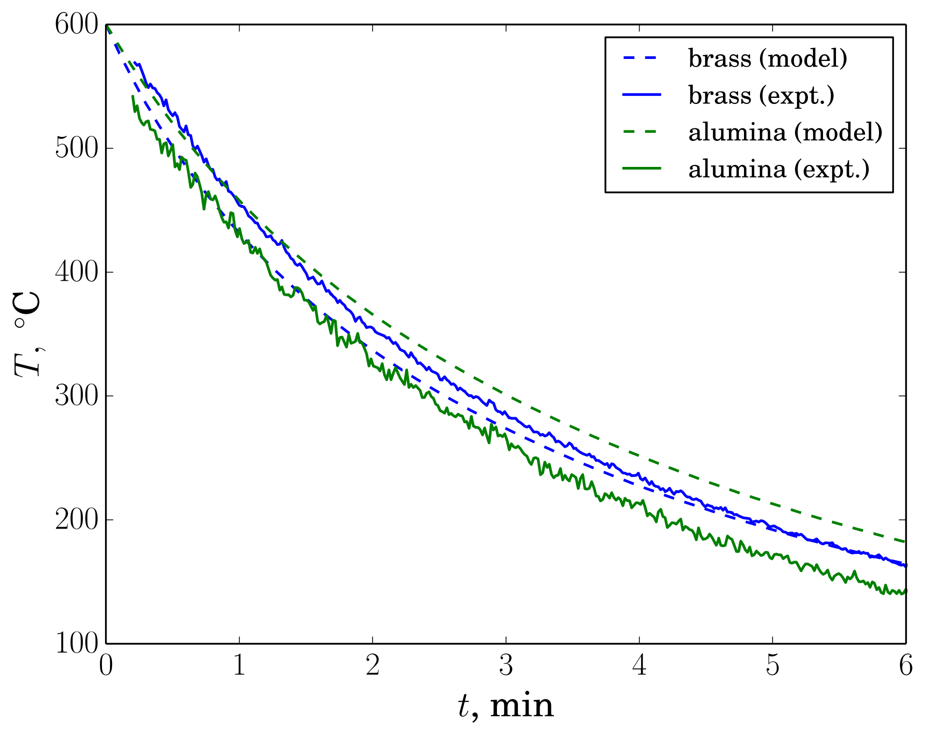


Figure 49. Temperature Decay for Cylindrical Slugs Cooled in Ambient Air from an Initial Temperature of 600 °C.

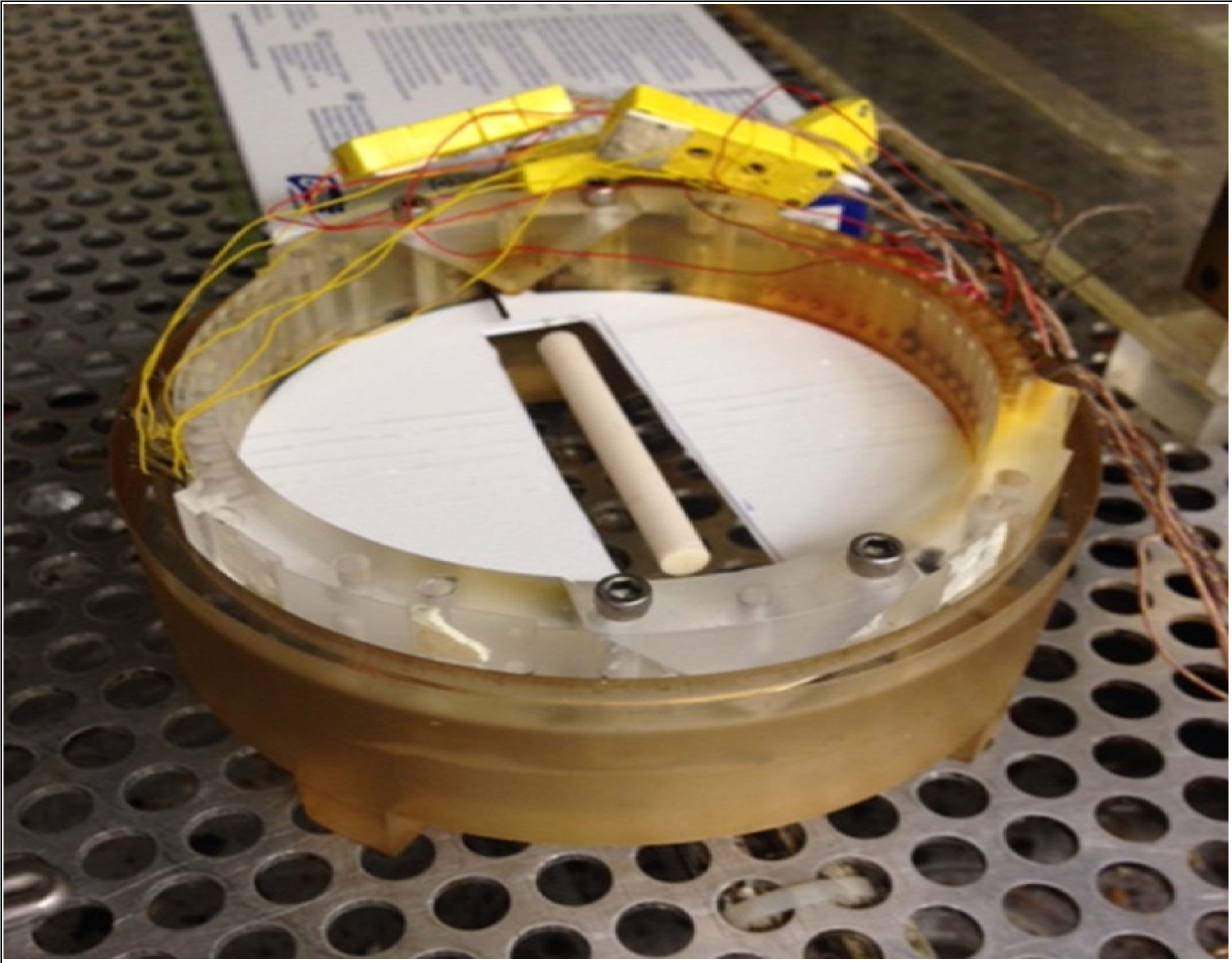


Figure 50. Experimental Configuration for Measuring Temperature Decay of Heated Slugs. An 80 mm Long Alumina Slug is Shown.

We then performed experiments with slugs of the various materials and lengths. At this point, the supply of fabrics used in the previous experiments had been depleted. Using SRM 1196 cigarettes, we identified new fabrics for which at least some ignitions occurred. Note that the new fabrics were not identical to the prior fabrics, and the results of the slug tests could not be related to the prior results, only to the performance of the SRM 1196 cigarettes on these new fabrics. In this feasibility assessment, only a few replicates were performed. Table 8 presents the most indicative data.

The first experiments with the uncovered slugs on the flat substrate were not successful. The experiments with the 80 mm brass slugs resulted in no ignitions up to 525 °C. The slugs were too heavy and collapsed the charring substrates. Since the 80 mm stainless steel rods were even heavier, no experiments were conducted with them. Experiments with the 40 mm stainless steel rods sometimes resulted in some charring and smoke, but no sustained ignitions, at temperatures up to 650 °C. Above this temperature, the slugs were regularly collapsing into the substrate.

Using a different fabric that gave rise to some, but not all ignitions with SRM 1196 cigarettes in the covered crevice configuration, a similar pattern was observed for the 20 mm and 40 mm stainless steel rods. At 650 °C, there was some charring and smoking, but no sustained ignition. At 700 °C, the slug descended into the melted foam. The lighter, alumina slugs initiated some charring and smoke generation at 650 °C, but did not initiate sustained smoldering even at 725 °C; they did not fall into the foam. It would be worthwhile to perform additional experiments with a flatter alumina slug.

The stainless steel tubes were the lightest of the slugs tested. However, their thermal inertia was too low. When the heaviest (80 mm) tubes were taken from the oven at 500 °C and placed on the inert substrate, the highest peak interface temperatures were only 170 °C, and the interface temperature fell to about 50 °C in a little over a minute. This discouraged further testing of the tubes.

Table 8. Ignitions from Exploratory Tests with Slugs on Reactive Substrates.

			Flat, uncovered			Flat, covered			Crevice, covered		
Material	Length (mm)	T (°C)	Fabric	Igns./ Exps.	% Igns.	Fabric	Igns./ Exps.	% Igns.	Fabric	Igns./ Exps.	% Igns.
SRM 1196			A	1/4	25						
303 SS rod	40	500	A	0/4[a]	0						
303 SS rod	40	550	A	0/4[a]	0						
303 SS rod	40	600	A	0/4[a]	0						
303 SS rod	40	625	A	0/4[a]	0						
303 SS rod	40	650	A	0/4[a]	0						
303 SS rod	40	700	A	1/4[b]	25						
SRM 1196									C	4/8	50
303 SS rod	20	600							C	0/8	0
303 SS rod	20	650							C	0/8[a]	0
303 SS rod	40	650							C	0/4[a]	0
303 SS rod	40	700							C	0/4[b]	0
alumina	20	675							C	0/4	0
alumina	20	700							C	0/4	0
alumina	20	725							C	0/4	0
SRM 1196						two B	4/4	100			
303 SS rod	20	600				two B	1/4	25			
303 SS rod	20	650				two B	4/4	100			
303 SS rod	40	650				two B	3/4	75			
303 SS rod	40	700				two B	4/4	100			
alumina	20	600				two B	2/4	50			
alumina	20	650				two B	3/4	75			

[a] Local smoldering initiated, but did not spread or sustain.

[b] The slug melted the foam and descended into the cavity.

6.4.3 Moving Hot Spot

To gain additional insight into the importance of a stationary hot spot relative to a similar hot spot that was moving at approximately the linear burning rate of the cigarette coal. A 27 mm cartridge heater was placed inside an 80 mm long stainless steel sleeve, laid on the substrate and heated. The target peak temperatures were 570 °C for the flat configurations and 430 °C for the crevice configuration. (cf. Table 2.) Once the target temperature had been reached, the operator gently held the sleeve and carefully pulled on the heater wires, advancing the heater stepwise every minute, with each step being approximately 5 mm. This was slightly faster than the linear burning rate for an SRM 1196 cigarette on the flat substrate and double the cigarette's linear burning rate in the crevice configuration.

The results of these moving cartridge tests were compared with (a) tests with the SRM 1196 cigarettes and (b) tests in which the same 27 mm heater, inside a 40 mm sleeve, was not moved. There was significant difficulty finding fabrics which led to some but not all ignitions with the SRM 1196 cigarettes and qualitatively similar cigarette ignition percentages with the static and moving cartridge heaters. Note that some experiments were also performed with the heater covered on the flat substrate.

Table 9 compiles the results of the better of these experiments. Figure 51 and Figure 52 (repeated from Figure 27) show examples of the thermal profiles in the two configurations.

Table 9. Comparison of Experiments with a Moving Cartridge Heater.

Configuration	Ignition Source	Moving?	Fabric	Igns./Exps.	% Ignitions
Uncovered flat	SRM 1196	---	D	1/4	25
	27 mm CH	Y	D	0/4	0
	27 mm CH	N	D	---	---
	SRM 1196	---	A	1/4	25
	27 mm CH	Y	A	---	---
	27 mm CH	N	A	2/28	7
Covered flat	SRM 1196	---	two B	4/4	100
	27 mm CH	Y	two B	8/8	100
	27 mm CH	N	two B	8/8	100
	SRM 1196	---	A	1/4	25
	27 mm CH	Y	A	---	---
	27 mm CH	N	A	---	---
Covered crevice	SRM 1196	---	C	4/8	50
	27 mm CH	Y	C	0/12	0
	27 mm CH	N	C	0/12	0
	SRM 1196	---	E	0/8	0
	27 mm CH	Y	E	0/8	0
	27 mm CH	N	E	0/8	0

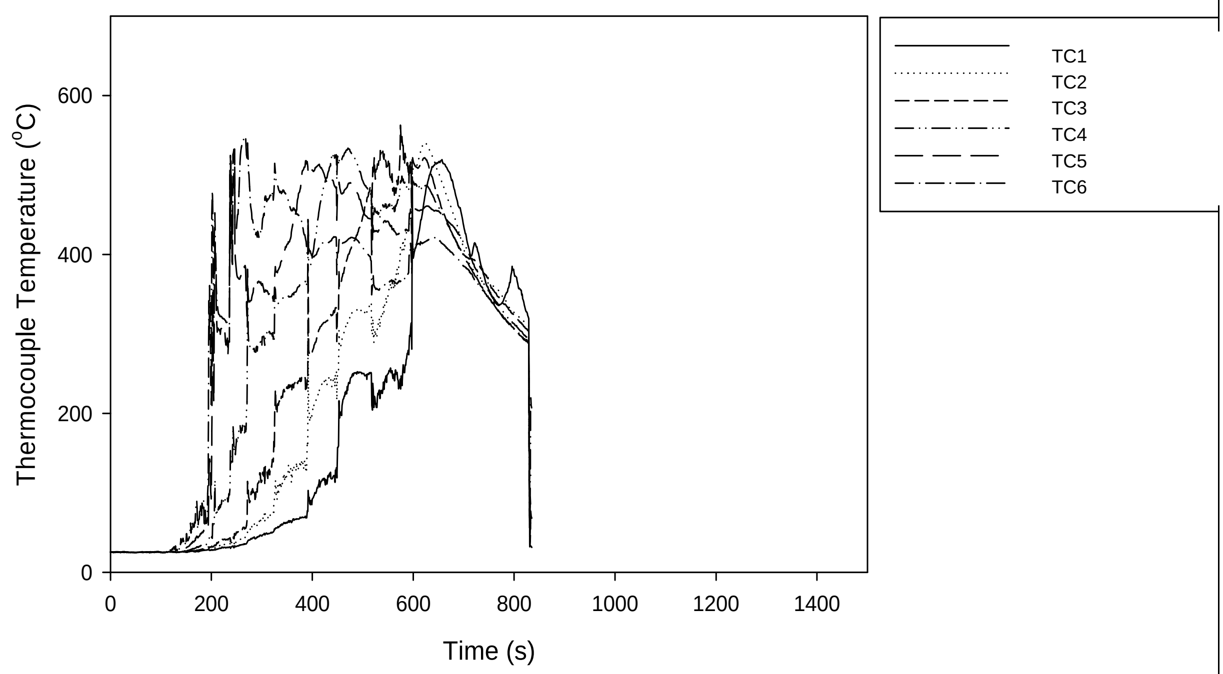


Figure 51. Temperature Measurements for an Uncovered Moving Cartridge Heater on a Flat Reactive Substrate.

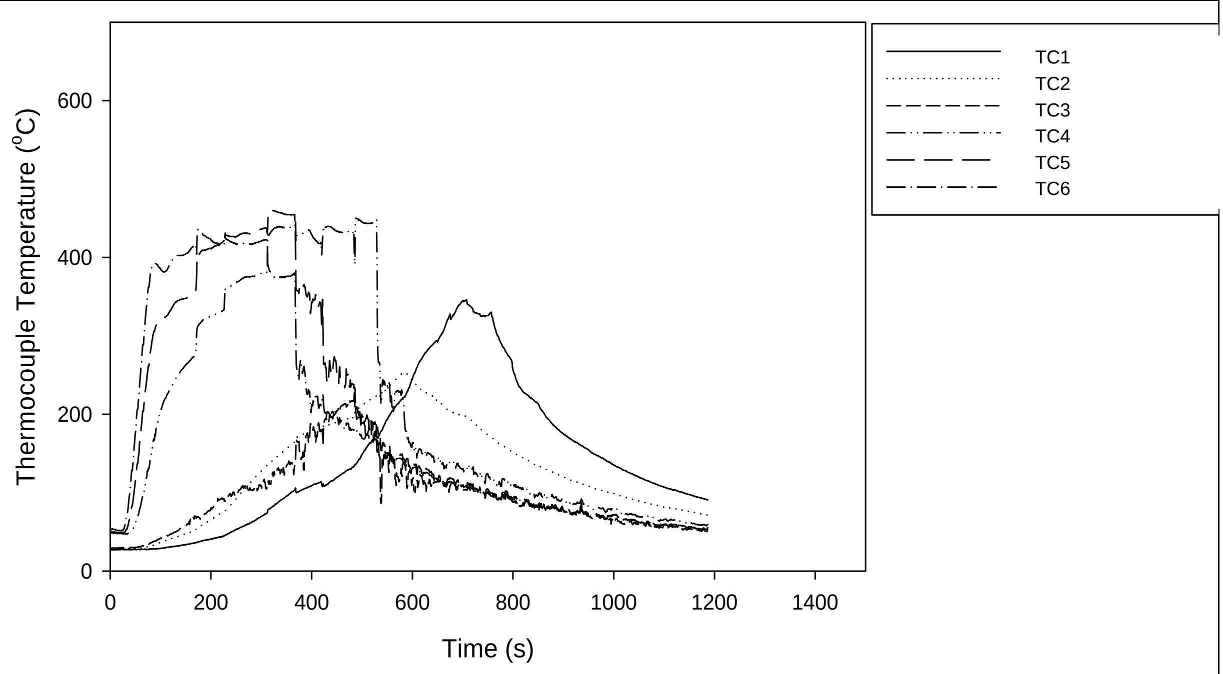


Figure 52. Temperature measurements for a Covered Moving Cartridge Heater on a Crevice Reactive Substrate.

In just these two Figures, there is a wide variety of peak shapes. This and the occasional low temperature peaks are due to changes in the thermal contact with the thermocouple beads, which is exacerbated by the periodic pressure applied to the sleeve as part of the cartridge moving process. It is possible to find encouragement from the ignition results in Table 9 that a further search for fabrics, coupled with fine tuning of the cartridge heater and its movement process, might lead to at least qualitative agreement between ignition percentages from the moving hot spot and the cigarette. However, this would be a time-consuming effort, and the product would still impose cost and operational burdens on the testing required in 16 CFR part 1632.

6.5 Results of Screening Tests

As guidance for the research leading to candidate ignition sources that are equivalent to the SRM 1196 cigarettes, we were seeking answers to the five questions posed in Section 6.1. The research reported here has provided these answers.

1. For both igniting and non-igniting tests, what is the time-evolving temperature profile (local thermal condition) at the interface of a candidate ignition source and a test substrate?

   We devised a thermocouple array that was generally able to follow the temperature profile at the interface between the ignition source and the substrate. There are factors that affect the repeatability of the profile and the ability to measure it, e.g., irregular thermocouple contact with the surface due to distortions of the surface and the ignition source.

2. To what extent is the potential for substrate ignition sensitive to the peak temperature and the duration of the elevated temperature of the ignition source?

   The sensitivity is significant and goes beyond the concept that a higher source temperature is more likely to lead to ignition. In a number of experiments, the substrate began to smoke, but before smoldering was sustained, the ignition source fell through the charred fabric, melted the foam, and fell into the cavity. Thus, too high a source temperature can be counterproductive.

3. Can a stationary ignition source lead to local thermal conditions and ignition propensity that are similar to those of a moving hot spot?

   The data indicate that this is possible. Demonstrating true equivalence of ignition propensity requires further refinement of the candidate ignition source and experiments with a range of substrate materials.

4. Can the local thermal conditions and cigarette ignition propensity be matched by a stationary hot spot that is *not* continuously heated?

   The data are promising, but the similarity of ignition propensity remains to be demonstrated, as discussed below.

5. To what extent does a chemical interaction between the ignition source and the substrate affect ignition propensity?

This is more difficult to answer. Prior research had indicated that the smoldering of an uncovered cigarette and the initial smoldering of the substrate are sufficiently slow that enough fresh oxygen can reach the interface to support both oxidation processes. In the current study, the similarity of thermal profiles for experiments with cigarettes and with inorganic ignition sources of comparable hot spot length indicates that the competition for available oxygen is a secondary factor. This is less clear for experiments with the ignition source covered in the crevice configuration.

We have also developed information on a wide variety of candidate externally powered, self-powered, and pre-heated ignition sources. The following is a compilation of our findings.

- Testing on the inert brass substrate led to interface temperatures that were far lower than those measured on fabric/foam substrates. The only apparent value in such tests is for screening candidate ignition sources: if a candidate source cannot generate an interface temperature near or above that measured for an SRM 1196 cigarette, the candidate source is not likely to be able to ignite a reactive substrate.
- Cartridge heaters are useful for investigating differences in potential ignition source conditions. However, as expected, they are not a viable ultimate solution. The wiring makes it difficult to place the heater at the beginning of a test. During a test, the wiring can accidently move the heater, especially on a non-flat surface.
- Operating cartridge heaters in the constant power mode was preferable to operating in the constant temperature mode. A burning cigarette is similar to a constant power source, if the supply of oxygen is constant. Thus, it is not surprising that the initial temperature ramp rate in this mode more closely approximates that of an actual cigarette.
- Powering the ignition source with on-board batteries is attractive. However, with current battery technology, this type of device could not reach the needed temperatures and would be quite expensive.
- Mixing two liquids that react exothermically introduces a significant level of complexity into routine testing. A housing containing pre-metered ampules of the reagents would be necessary, along with a repeatable means for breaking them and causing the liquid to mix. For safe operation, the housing would need to withstand both the breaking process and the high temperatures needed for substrate ignition.
- Methenamine pills are designed to initiate flaming, not smoldering. Research would be needed to assure steady burning at a lower temperature.
- Exothermally intumescent materials (e.g., “black snakes”) curl excessively and unrepeatably, resulting in their not maintaining uniform thermal contact with the test substrate.
- The tested willow charcoal drawing sticks burned hot enough on the inert substrate, but the burn rate was slow, and the material wasn’t uniform. Since charcoal is generated from a natural material and this version is designed for a purpose other than ignition testing, there is likely to be variation over time.
- The four versions of cotton rolls burned with peak temperatures that were too low.

- The diamond braided cotton rope with its core removed burned with peak interface temperature and ignition rate that were very much like those of the SRM 1196 cigarette. However, the interface temperature profiles indicated that the contact of the rope with the substrate surface was less than consistent. A more significant caution is that we were only able to locate a single vendor, and even there it is now a special-order product. As for any reactive ignition source, its implementation would require comprehensive specifications to ensure uniformity within a single batch and among batches manufactured at different times. These specifications and the sensitivity of their ignition propensity to their precision would need to be quantified through testing of a large number of specimens, each of which is to be characterized prior to being ignited.
- Solid slugs also were potentially successful candidate ignition sources, especially for testing on flat surfaces.
- Moving a cartridge heater along the surface of a reactive substrate could result in a thermal profile similar to that of an SRM 1196 cigarette. However, the mechanics of moving the heater are not practical. Manual motion is jerky, the rate of movement is unlikely to be repeatable, and performing this for 18 concurrent specimens in 16 CFR part 1632 is unwieldy. It is also difficult to maintain consistent thermal contact with the substrate. A mechanical drive is likely to be costly and introduces the routine testing difficulties associated with heater wires.

In summary, the most promising approach involves slugs. The cored cotton rope gave promising results as well. However, its potential for not being available and reproducible makes it a risky candidate.

7 DEMONSTRATING EQUIVALENCE TO SRM 1196 CIGARETTES

7.1 Two-task Process

Demonstrating the ability of a slug to match the ignition performance of the SRM 1196 cigarette on current and future substrates relies on success with two tasks.

1. Identification of a set of substrate materials that encompass the ignition performance of the range of materials used today and their logical derivatives. If the performance in the test is tied to performance in use, as is the case in 16 CFR part 1632, where the actual product is tested, then the test results for future new materials will be accurate.

   It is recognized that commercial fabrics and padding materials have some degree of nonuniformity that can affect their susceptibility to smoldering ignition. Therefore, after a suitable screening process, large lots of the selected fabrics and foam need to be acquired and the variability of their susceptibility to cigarette ignition quantified.

2. Identifying a slug design with the set of combined properties that results in an assessment of equivalency to the SRM 1196 cigarettes on the substrates identified in Task 1. The properties include:
   a. Choice of material, taking into consideration its thermal stability, re-usability, and thermal inertia;
   b. Dimensions;
   c. Shape, which affects its contact with the substrate surface; and
   d. Mass, which could be independent of density, e.g., by using a tube instead of a solid rod.

   Also of importance is finding the optimal initial temperature of the slug.

   It is desirable, but not necessary, that a single slug design provide equivalency in all test configurations.

At this point in the project, CPSC staff and NIST staff agreed that the initial focus should be on an ignition source for use in 16 CFR part 1632. The testing under this regulation involves nominally flat surfaces, with both covered and uncovered cigarettes. Nonetheless, it was efficient to screen the candidate materials in the crevice configuration concurrently, rather than re-start the screening process at a later date.

7.2 Materials Screening

The objective for this task was to identify a set of fabric/foam substrates that ignited some, but not all, of the time when a lit SRM 1186 cigarette was placed on them. The materials were to be indicative of those that might be used in the top surfaces of mattresses and in comforters.

To demonstrate equivalency, the number of substrates should be considerable for two reasons.

1. The fabric/foam combinations in use today meet the cigarette ignition resistance requirements of 16 CFR part 1632. A surrogate ignition source should not ignite them either. However, since these materials rarely, if ever, ignite in the test, they themselves are not candidates for demonstrating the equivalency of an alternate ignition source. The materials to be screened should span the range of properties of the current mattress materials, while igniting some, but not every time, with an SRM 1196 cigarette.
2. The shapes of the thermal interface profiles for non-reacting ignition sources were not identical to the profiles for cigarettes. Multiple test substrates are needed in order to minimize the potential for placing undue emphasis on an incorrect feature of the profile on a single substrate.

As a starting point, the test set would include two FPU foams and four to six fabrics for each configuration (flat surface with covered and uncovered cigarettes). Additional successful materials should be identified, since the large batches of materials needed to establish equivalency might not match the ignition propensity of the samples obtained for the screening. It might well require 10 fabrics "passing" the screen tests to obtain four that work in large batch. This set of successful fabrics should have diverse physical properties.

Fabrics and foams are not manufactured for consistency of susceptibility to ignition. There are gradations within a production run. Thus, once the screening has identified a set of potential candidates, it will be necessary to do a significant number of replicate tests. This would then be followed by an Interlaboratory Evaluation (ILE), involving additional replicate testing. The ILE would establish statistical values for the equivalence and the reproducibility of testing using the new ignition source(s).

Fortunately, recent research has identified properties of FPU foams that affect the extent of smoldering [35] and, probably, the foam's contribution to smoldering ignition. Thus, large, relatively uniform batches of FPUF can be ordered. One FPUF that is moderately prone to ignition and a second that is highly prone to ignition should suffice.

To begin the screening process for fabrics, we purchased approximately 10 m^2 to 30 m^2 of 36 fabrics. All were nominally 100 % cellulosic in content. We used specimens from four batches of FPUF, all of which had shown similar mass loss percentages following ignition to smoldering. We tested substrates with a single layer of each of the fabrics over the foam. We also tested substrates with two layers of 18 of the fabrics, for a total of 54 substrates. This amounted to a total of 856 tests. Of these, 414 were conducted in the flat configuration with the cigarette uncovered, 192 in the flat configuration with the cigarette covered by a cotton sheet, and 250 were in the crevice configuration with the cigarette covered. For all tests, the ignition source was the SRM 1196 cigarette.

Table 10 summarizes the results of this screening. Some fabrics were not tested in all three configurations. Experience had indicated that the flat and uncovered configuration is typically (but not always) the least ignition prone, and that the crevice/covered cigarette configuration is often the most ignition prone. The flat/covered configuration is often in the middle. In addition, if a single layer of a cotton fabric does not ignite in every experiment, then two layers of that fabric is more likely to ignite. For those relatively few fabrics which were ignited, Table 10 supports this hierarchy. These observations allowed for a reduction in the total number of tests required and most of the empty cells in the Table.

The substrates for which some ignitions, but not 100 % occurred are highlighted in red in the Table. These total only 2 of the configurations involving the flat uncovered substrates, 4 of the flat, covered substrates, and 14 of the covered crevice substrates.

Table 10. Summary of Fabric Screening Test Results Using SRM 1196 Cigarettes.

Fabric	Number of Layers	Number of Ignitions/Number of Experiments		
		Flat, Uncovered	Flat, Covered	Crevice, Covered
Blue Denim	1	**19/76**	**5/20**	*
Blue Denim	2	**8/20**	**10/12**	*
Black Floral	1	0/4	*	*
Black Floral	2	*	0/8	*
Yellow Floral	1	*	0/4	*
Tan/Blue Stripes	1	4/4	*	*
White/Blue Stripes	1	0/4	*	**1/20**
White/Blue Stripes	2	0/4	*	*
White	1	0/28	0/4	0/8
White	2	0/4	*	*
Black Velvet	1	0/16	0/8	**19/24**
Black Velvet	2	0/4	**3/8**	*
White Twill	1	0/32	0/16	**7/20**
White/Blue Ticking	1	0/12	0/8	**11/20**
White/Blue Ticking	2	0/4	0/8	*
Eggshell Twill	1	0/4	0/12	0/4
Tan Flannel	1	0/4	*	**3/8**
Tan Flannel	2	0/4	*	*
White Terrycloth	1	0/12	0/8	*
White Terrycloth	2	0/4	*	*
Brown Burlap	1	0/12	*	**4/8**
Brown Burlap	2	0/4	*	*
White Waffle	1	0/12	*	4/4
White Waffle	2	*	0/8	*
Natural Felt	1	14/14	8/8	*
Khaki Denim	1	0/8	0/4	**6/14**
Khaki Denim	2	*	0/12	*
Natural Denim	1	*	*	4/4
Natural Denim	2	*	0/12	*
White Denim	1	*	*	4/4

Fabric	Number of Layers	Number of Ignitions/Number of Experiments		
		Flat, Uncovered	Flat, Covered	Crevice, Covered
White Denim	2	*	**11/16**	*
Khaki Twill	1	0/4	*	**6/8**
Khaki Twill	2	0/4	0/4	*
Blue Twill	1	0/4	*	**2/8**
Blue Terrycloth	1	0/4	*	**3/8**
White Stripe Seersucker	1	0/4	0/4	0/4
Black Stripe Seersucker	1	0/4	*	0/8
White Oxford	1	0/4	*	0/8
Light Blue Oxford	1	0/4	*	0/8
Unbleached Osnaburg	1	0/4	*	0/8
White Flannel	1	0/4	*	0/8
Black + White Plaid Flannel	1	0/16	*	8/8
Black + White Plaid Flannel	2	0/4	0/4	
Gray Flannel	1	0/4	*	**1/8**
Green Corduroy	1	0/4	*	**7/8**
Green Corduroy	2	0/4	0/4	*
Brown Corduroy	1	8/8	*	*
Green Flannel	1	0/8	*	**3/12**
Green Flannel	2	0/4	*	*
Brown Flannel	1	0/4	*	**1/8**
Dark Blue Denim	1	4/4	*	*
White Cover Cloth	1	0/4	*	*
White Cover Cloth	2	0/4	*	*
Natural Cotton Ducking	1	16/16	*	*

* Not tested

7.3 THE NEXT STEPS

7.3.1 Screening of Additional Fabrics

Of the 54 substrates, too few met the initial screening requirements to proceed further. It would be necessary to expand the list of vendors and to identify an extensive set of additional fabrics that would also be likely to remain in production for at least another year. This process would continue until nominally 10 fabrics generated some, but not all ignitions on each of two foams.

7.3.2 Consensus on Equivalence

It is unlikely that the outcome of parametric testing would be a perfect match between the ignition propensity of a candidate surrogate ignition source and the SRM 1196 cigarette on all the tested substrates. Therefore, there needs to be pre-agreement on the criterion for satisfactory equivalence.

7.3.3 Parametric Testing

The parameters to be examined to refine the ignition source(s) and demonstrate equivalence to the SRM 1196 cigarettes include:

- Materials: Foam (2) , fabric (10, although perhaps half of these might be discarded early in the testing);
- Configuration: ignition source covered/uncovered (2);
- Slug properties: materials (4), length (3, probably reducible to 2 early in the testing), cross-section (3; round, square, rectangular);
- Initial slug temperature (minimum of 3 per configuration); and
- Reference ignition source: SRM 1196.

Based on prior experience, at least 20 replicate tests of each combination would be needed due to the variability of the materials and test-to-test variation in the slug's initial temperature and its placement on the substrate.

Following identification of at least one candidate each being equivalent to the SRM 1196 cigarette covered or uncovered, these candidates would be tested on current substrates that are known to be "passes" or fails."

In all, this amounts to at least 30,000 tests. With a judicious hierarchy of testing, it might be possible to reduce this somewhat. If the testing were performed in the current laboratory and without using the thermocouple array, it would take at least 18 months of nonstop testing to complete each 10,000 tests. The thermocouple array provides information on the true value of the slug/substrate interface temperature at the beginning of a test. However, such testing is considerably slower, and it would take approximately three years to complete each 10,000 tests.

There are also logistical considerations in such a test program. The volume of FPUF needed for 10,000 tests is approximately 20 m^3; the fabric area is approximately 400 m^2.

This page intentionally left blank.

8 RECOMMENDATIONS

The process necessary to determine whether a slug could match the ignition propensity of SRM 1196 cigarettes (for each test configuration in 16 CFR part 1633) is long and costly. Of even more importance, there is no assurance that the criterion for equivalence would be met. NIST staff do not recommend pursuit of this effort.

Subsequent to reaching this conclusion, NIST staff has determined that it is currently possible to manufacture additional SRM 1196 cigarettes and that there is at least one manufacturer willing and able to do so.

Therefore, NIST staff recommends that arrangements commence to obtain a new supply of SRM 1196 cigarettes. The new supply should last at least 10 years at the current demand.

The page intentionally left blank.

9 REFERENCES

1. Hall, J.R., 2013, "The Smoking-Material Fire Problem," National Fire Protection Association, Quincy, MA.

2. 16 Code of Federal Regulations, Part 1632, 1972, “Standard for the Flammability of Mattresses and Mattress Pads.”

3. "Technical Bulletin 116, Requirements, Test Procedure, and Apparatus for Testing the Flame Retardance of Upholstered Furniture," 1980, Bureau of Home Furnishings and Thermal Insulation, State of California.

4. "Technical Bulletin 117, Requirements, Test Procedure, and Apparatus for Testing the Flame and Smolder Resistance of Upholstered Furniture," 2014, Bureau of Home Furnishings and Thermal Insulation, State of California.

5. NFPA 260, "Standard Methods of Tests and Classification System for Cigarette Ignition Resistance of Components of Upholstered Furniture," 2009, National Fire Protection Association, Quincy, MA.

6. NFPA 261, "Standard Method of Test for Determining Resistance of Mock-Up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes," 2009, National Fire Protection Association, Quincy, MA.

7. ASTM E 1352, "Standard Test Method for Cigarette Ignition resistance of Mock-Up Upholstered Furniture Assemblies," 2002, ASTM International, West Conshohocken, PA.

8. ASTM E 1353, "Standard Test Methods for Cigarette Ignition Resistance of Components of Upholstered Furniture," 2002, ASTM International, West Conshohocken, PA.

9. “Fabric Classification Test Method,” 1990, Upholstered Furniture Action Council, High Point, NC. http://www.ufac.org/method1.htm

10. Loftus, J.J., June 18, 1971, “Results of Temperature measurements Made on Burning cigarettes and Their Use as a Standard Ignition Source for Mattress Testing,” Memorandum to L.J. Sharman, National Bureau of Standards, Washington, D.C.

11. "Toward a Less Fire-Prone Cigarette," 1987, Final Report to the Congress, Technical Study Group on Cigarette and Little Cigar Fire Safety, Cigarette Safety Act of 1984.

12. U.S. Consumer Product Safety Commission, 1993, “Overview: Practicability of Developing a Performance Standard to Reduce Cigarette Ignition Propensity,” Report No. **1**, Technical Advisory Group, Fire Safe Cigarette Act of 1990.

13. ASTM E 2187, “Standard Test Method for Measuring the Ignition Strength of Cigarettes,” 2009, ASTM International, West Conshohocken, PA.

14. Gann, R. G., and Hnetkovsky, E. J., 2009, "Modification of ASTM E 2187 for Measuring the Ignition Propensity of Conventional Cigarettes," NIST TN 1627, National Institute of Standards and Technology, Gaithersburg, MD.

15. Gann, R. G., Harris, J., R.H., Krasny, J. F., Levine, R. S., Mitler, H. E., and Ohlemiller, T. J., 1987, "The Effect of Cigarette Characteristics on the Ignition of Soft Furnishings," Volume 3 Technical Study Group Cigarette Safety Act of 1984, NBS TN 1241, National Bureau of Standards, Gaithersburg, MD.

16. Robbins, A. P., and Gann, R. G., 2011, "Potential Alternate Smoldering Ignition Sources: Literature Review with Analysis," NIST TN 1710, National Institute of Standards and Technology, Gaithersburg, MD.

17. Cleary, T., 2009, "Results from a Full-Scale Smoke Alarm Sensitivity Study," *Suppression and Detection Research Application: A Technical Working Conference, 13th Annual. SUPDET 2009. Proceedings*, Fire Protection Research Foundation, Orlando, FL.

18. Pitts, W. M., 2007, "Ignition of Cellulosic Fuels by Heated and Radiative Surfaces," NIST Technical Note 1481, National Institute of Standards and Technology, Gaithersburg, MD.

19. Bukowski, R. W., Peacock, R. D., Averill, J. D., Cleary, T. G., Bryner, N. P., Walton, W. D., Reneke, P. A., and Kuligowski, E. D., 2008, "Performance of Home Smoke Alarms, Analysis of the Response of Several Available Technologies in Residential Fire Settings," TN 1455-1, National Institute of Standards and Technology, Gaithersburg, MD.

20. Kashiwagi, T., 1979, "Experimental Observation of Radiative Ignition Mechanisms," *Combustion and Flame*, 34, pp. 231-244.

21. BS 4790, 1987, "Method of Determination of the Effects of a Small Source of Ignition on Textile Floor Coverings (Hot Metal Nut Method)," British Standards Institution, London, UK.

22. Beyler, C. L., Fay, T., Gratkowski, M., Campbell, B., and Hartman, J. R., 2006, "Ignition Studies of Cerium Nitrate Treated Towels," *Fire and Materials*, 30, pp. 223-240.

23. Tao, W., 2002, "Memorandum regarding the Development of a Surrogate for the Standard Cigarette Ignition Source – Status Report, April 2002, Consumer Product Safety Commission," Recipient: Neily, M., U.S. Consumer Product Safety Commission, Washington, D.C.

24. Kinbara, T., Endo, H., and Sega, S., 1966, "Combustion Propagation through Solid Materials I – Downward Propagation Along a Thin Vertical Sheet of Paper," *Combustion and Flame*, 10(1), pp. 29-36.

25. Suuberg, E. M., Milosavljevic, I., and Lilly, W. D., 1994, "Behavior of Charring Materials in Simulated Fire Environments," NIST-GCR-94-645, National Institute of Standards and Technology, Gaithersburg, MD.

26. Kinbara, T. 1967, "Downward Propagation of Smoldering Combustion through Solid Material," *Proceedings of the Combustion Institute*, 11, pp. 525-531.

27. Anderson, M. K., Sleight, R. T., and Torero, J. L., 2000, "Igintion Signatures of a Downward Smolder Reaction," *Experimental Thermal and Fluid Science*, 21, pp. 33-40.

28. Cagliostro, D. E., Riccitello, S. R., Clark, K. L., and Shimizu, A. B., 1975, "Intumescent Coating Modeling (for Thermal Protection)," *Journal of Fire and Flammability*, 6, pp. 205-221.

29. FF 1-70, 2000, "Standard for the Surface Flammability of Carpets and Rugs," U.S. Consumer Product Safety Commission, Bethesda, MD.

30. Salig, R., 1982, "Smoldering Behavior of Upholstered Polyurethane Cushioning and Its Relevance to Home Furnishings Fires," Master of Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA.

31. Waymack, B. E., Kellogg, D. S., McRae, D. D., and Dwyer, R. W., 1997, "Watts in a Cigarette: Thermophysical Properties of Smoldering Cigarettes," *Tobacco Science*, 41, pp. 74-81.

32. Loftus, J. J., 1978, "Back-Up Report for the Proposed Standard for the Flammability (Cigarette Ignition Resistance) of Upholstered Furniture," PFF 6-76, NISTIR 78-1438, National Bureau of Standards, Gaithersburg, MD.

33. Sherwood, T. S., Issac, J. C., and Jones, J. S., 2006, "Semi-Empirical Model using Radiant Coal Power to Predict Cigarette Ignition Strength as Measured by Extinction Test," *Fire Technology*, 42(3), pp. 233-251.

34. Krasny, J. F., Allen, P. J., Maldonado, A., and Juarez, N., 1981, "Development of a Candidate Test Method for the Measuremnet of the Propensity of Cigarettes to Cause Smoldering Ignition of Upholstered Furniture and Mattresses," NISTIR 81-2363, National Bureau of Standards, Gaithersburg, MD.

35. Zammarano, M., Kramer, R.H., Matko, S., Smith, M., Mehta, S., Gilman, J.W., and Davis, R.D., 2012, “Factors Affecting the Smoldering Performance of Polyurethane Foam,” NIST Technical Note 1747, National institute of Standards and Technology, Gaithersburg, MD.

36. Ohlemiller, T. J., Villa, K. M., Braun, E., Eberhardt, K. R., Harris, J., R.H., Lawson, J. R., and Gann, R. G., 1992, "Test Methods for Quantifying the Propensity of Cigarettes to Ignite Soft Furnishings," Report No. 2, Technical Advisory Group, Fire Safe Cigarette Act of 1990 and NIST Special Publication 851, National Institute of Standards and Technology, Gaithersburg, MD.

37. Gann, R.G., Steckler, K.D., Ruitberg, S., Guthrie, W.F., and Levenson, M.S., 2001, “Relative Ignition Propensity of Test Market Cigarettes,” NIST Technical Note 1436, National Institute of Standards and Technology, Gaithersburg, MD.

38. Ohlemiller, T. J., and Rogers, F. E., 1980, "Cellulosic Insulation Material II, Effect of Additives on Some Smolder Characteristics," Combustion Science and Technology, 24(3-4), pp. 139-152.

39. Sandusky, H.W., 1976, “A Computer-Simulated Cigarette Model for Use in the Development of Less Hazardous Cigarettes,” Ph.D. Thesis, Princeton University.

40. Tao, W., 2003, “Development of a Potential Surrogate for the Standard Cigarette Ignition Source,” Consumer Product Safety Commission, Bethesda, MD.

41. Mills, A.F., 1999, *Heat Transfer*, Prentice Hall, Upper Saddle River, NJ.