Test Methods for Quantifying the Propensity of Cigarettes to Ignite Soft Furnishings

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Fire Safe Cigarette Act of 1990

Under the Cigarette Safety Act of 1984 (P.L. 98-567), the Technical Study Group on Cigarette and Little Cigar Fire Safety (TSG) found that it is technically feasible and may be commercially feasible to develop a cigarette that will have a significantly reduced propensity to ignite furniture and mattresses. Furthermore, they found that the overall impact of such a cigarette on other aspects of the United States society and economy may be minimal.

Recognizing that cigarette-ignited fires continue to be the leading cause of fire deaths in the United States, the Fire Safe Cigarette Act of 1990 (P.L. 101-352) was passed by the 101st Congress and signed into law on August 10, 1990. The Act deemed it appropriate for the U.S. Consumer Product Safety Commission to complete the research recommended by the TSG and provide, by August 10, 1993, an assessment of the practicality of a cigarette fire safety performance standard.

Three particular tasks were assigned to the National Institute of Standards and Technology's Building and Fire Research Laboratory:

- develop a standard test method to determine cigarette ignition propensity,
- compile performance data for cigarettes using the standard test method, and
- conduct laboratory studies on and computer modeling of ignition physics to develop valid, user-friendly predictive capability.

Three tasks were assigned to the Consumer Product Safety Commission:

- design and implement a study to collect baseline and follow-up data about the characteristics of cigarettes, products ignited, and smokers involved in fires,
- develop information on societal costs of cigarette-ignited fires, and
- in consultation with the Secretary of Health and Human Services, develop information on changes in the toxicity of smoke and resultant health effects from cigarette prototypes.

The Act also established a Technical Advisory Group to advise and work with the two agencies.

This report is one of six describing the research performed and the results obtained. Copies of these reports may be obtained from the **U.S. Consumer Product Safety Commission, Washington, DC 20207.**

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EXECUTIVE SUMMARY

Cigarette ignition of soft furnishings (upholstered furniture and mattresses) continues to be the leading cause of fire deaths in the United States. In 1990, the nation experienced 1220 lost lives, 3358 serious civilian injuries, and $400 million in direct property loss from 44,000 cigarette-initiated fires in structures. This publication describes the research performed and the results obtained in responding to two tasks under the Fire Safe Cigarette Act of 1990 (P.L. 101-352):

> "(1) develop a standard test method to determine cigarette ignition propensity, and
>
> (2) compile performance data for cigarettes using the standard test method developed under paragraph (1)"

as part of an assessment of the practicability of developing a performance standard to reduce cigarette ignition propensity. This research builds on previous studies directed by the Technical Study Group (TSG) under the Cigarette Safety Act of 1984 (P.L. 98-567) and related work performed by the cigarette industry.

The principal content of the report is documentation of the selection, development and final form of two test methods for cigarette ignition propensity. They are intended to fulfill two potential roles: (a) the basis for a possible performance standard, and (b) assistance to the cigarette industry in meeting the goals of any such regulation and in quality assurance testing. Both methods have valid links (comparable to many current fire test methods) to many real-world fire scenarios of concern. Both incorporate most of the relevant physics and chemistry of such ignitions, while replicating the real-world hazard to differing extents. They are both performance tests, as contrasted with product design specifications. Both tests offer the use of a graded measure of performance, where acceptable levels can be set by the regulator. The research and this report do not address specific regulatory criteria.

The *Mock-Up Ignition Test Method* uses three types of simulated upholstery cushions, each with a different cigarette ignition susceptibility. Each 20 cm x 20 cm assembly (substrate) consists of a top layer of one of three weights of cotton duck fabric (#4, #6, and #10, in increasing order of ignition susceptibility); a 5 cm thick piece of a polyurethane foam; and, in the least susceptible substrate, a thin layer of thermoplastic film in between. Tests are conducted in a plastic enclosure to eliminate variability due to laboratory air currents. A test begins by placing a lit cigarette on the mock-up. The performance measure is whether or not the mock-up is ignited (char propagation over 10 mm from the burning tobacco column). Either self-extinction of the cigarette or the cigarette burning its entire length without igniting the mock-up assembly are counted as non-ignitions. A complete test series consists of 48 replicates of each cigarette on each substrate.

The *Cigarette Extinction Test Method* replaces the more complex substrate of the Mock-Up Ignition Test Method with standard cellulosic filter paper. Otherwise, the test procedure is similar. The three substrates used consist of 3, 10, or 15 layers of the paper. The test determines whether a selected substrate absorbs enough heat from the cigarette coal to extinguish the cigarette. Performance with this method was roughly correlated to prior direct measures of cigarette ignition propensity. Here, increased reproducibility of test materials is gained at the cost of direct simulation of the real-world fire scenario. Sixteen replicates of each cigarette are performed on each substrate.

Only flat substrates were selected, although many real-world ignitions are expected to occur in furniture crevices. The TSG studies showed a higher fraction of crevice ignitions for a cigarette of high ignition propensity, but no consistent difference in ignition susceptibility between the two configurations for cigarettes of moderate-to-low ignition propensity. Potential variability of contact between the cigarette coal and the surfaces of the crevice substrates introduces an operator dependence that is undesirable.

All testing is performed without externally-imposed air flow. This is operationally the simplest approach and is highly relevant. In the real world, the orientation of any flow relative to the cigarette coal is unknown but probably random. Many ignitions may occur deep in a crevice, and the air flow there is likely to be very small. While cigarette industry studies showed some cigarettes undergoing substantial changes in rankings of ignition performance under varying air flows, greater flow differences between mock-up and chair tests in the TSG studies did not preclude a good correlation between these two types of tests. The existence of this correlation strongly implies that there will be a real-world benefit in moving toward cigarettes which perform well in the two test methods developed here. Should further information on real-world ignitions indicate a significant fraction due to low ignition propensity cigarettes in external air flow conditions *at the ignition location*, it may be appropriate to supplement the results of the current methods with those of tests conducted in the presence of a comparable flow.

The two test methods were developed using experimental cigarettes manufactured by the cigarette industry for this purpose. The cigarettes varied widely in performance, from some having ignition propensities comparable to current commercial cigarettes to others that rarely or never ignited any of the test substrates in both this and cigarette industry studies.

The two methods were shown to be of useful reproducibility in a nine-laboratory study. The study involved cigarette industry, state and federal agency, and private testing laboratories, and conformed to ASTM guidelines. Five of the available experimental cigarettes were tested, based on their expected ignition performance.

The *repeatability* (a measure of variability within a laboratory) decreases as the square root of the number of replicates. Thus, for production quality assurance testing, a fine degree of resolution is possible. By contrast, the *reproducibility* (a measure of variability between laboratories) approaches a non-zero limit for a large number of replicates. Typically, for both of these test methods, the ASTM reproducibility limit of the percentage of ignitions or the percentage of cigarettes burning their full lengths on a given substrate was *ca.* 40 percent. This value defines the limit of resolution for use in any future regulations.

The study showed that the lab-to-lab variability of results was comparable to that for other fire test methods currently being used to regulate materials which may be involved in unwanted fires. The results were generally insensitive to the date and time of day of testing, the particular test enclosure used, and the operator skill level. All labs conformed sufficiently to the temperature and humidity criteria for the conditioning and test rooms that this was not an important factor in the results. The three substrates in each method were all statistically distinct from each other, as were the five cigarette types.

Since the results show that the methods can effectively differentiate the ignition propensities of various cigarettes with acceptable precision, specifications for the test materials were developed. All four types of materials were deemed likely to be available, with long-term consistency, in the foreseeable future. For the fabrics, the areal density and potassium ion content were determined to be the major parameters affecting ignition susceptibility. Analysis of within-lot samples, lot-to-lot samples, and samples from two manufacturers showed that the normal production variations were within the acceptable limits demonstrated in the interlaboratory study. There is a long history of a large demand for cotton duck fabrics for both commercial use and military procurement. The polyurethane foam is representative of foam products used in the residential furniture market. Experiments showed that the effect of expected foam property variations (within nominally similar formulations) is minimal. Differences between brands of purportedly the same polyethylene film resulted in a significant change in test method results. However, specification of the areal density should ensure use of a proper material. The filter paper is a long-time, high-purity standard material for numerous chemical methods. Variations in the areal density, thickness and thermal conductivity are minimal. It was estimated that "fresh" substrate materials did not age substantially over about 6 months or longer.

There are data to "calibrate" the methods at the high and low ends of the ignition propensity scale. The commercial cigarette data in the TSG studies establish an indication of performance for the cigarettes associated with then-current fire losses. In the two new test methods, this performance is seen as a large number of ignitions on the #4 cotton duck or full-length burning on the 15-layer paper substrate. This establishes the test results for the high ignition propensity end of the scale. The TSG work, the current research, and cigarette industry studies demonstrate that there are experimental cigarettes that never or rarely ignited a variety of substrates. In the two new test methods, this behavior is observed as few ignitions on the #10 cotton duck or few full-length burns on 3 layers of filter paper. In between these extremes, one would like to expect a reduced number of fires as fewer ignitions are measured in the laboratory. The TSG correlation of mock-up results with chair tests indicates that such results can be expected to be indicative of performance for significant portions of the real-world furniture population, at least for coarse changes in test performance. If considering small increments, however, one must keep in mind the accuracy limits of the methods as discussed above.

For a product standard, there is a preference at present for using the Mock-Up Ignition Test Method, because it is capable of better distinction among cigarettes of high ignition propensity. However, routine measurement of the relative ignition propensity of cigarettes is feasible using either of the two methods. The mock-up ignition method requires about 3 staff days to perform the 144 tests; the cigarette extinction method, with its simpler substrates and 48 tests, about 1 staff day. A rationale has been developed to reduce the number of tests for cigarettes of expected very high or very low ignition propensity.

It is common practice, upon development of a fire test method for professional use, to proceed with its adoption as a voluntary consensus standard in either the ASTM or the National Fire Protection Association (NFPA). This report contains sufficient documentation of the two test methods and interlaboratory evaluations of each. Thus, all necessary materials for initiating the standardization process are now available.

Twenty current commercial cigarettes were tested using the two methods. Fourteen of these were the best-selling packings, comprising nearly 40 percent of total sales in 1990. These cigarettes did not vary widely in their physical characteristics. They showed consistent ignitions on all substrates using the Mock-Up Ignition Method and consistently burned their full length on all substrates tested in the Cigarette Extinction Method.

Also tested were six other packings, each having one or two physical parameters (*e.g.*, low circumference, paper porosity, tobacco density) which deviate from the best-sellers in a direction which prior research would suggest as likely to lower ignition propensity. All six of these packings showed reduced ignition propensity in the Mock-Up Ignition Test Method. Four of these packings rarely ignited the most difficult-to-ignite substrate; the other two ignited it in 40-70% of the tests. Three of the four packings showed reduced ignition propensity on the middle substrate as well. While the Cigarette Extinction Test Method is less sensitive to changes in ignition propensity, three of the packings showed markedly fewer full-length burns. All these differentiations are outside the variability of the test methods. The average values of tar, nicotine, and carbon monoxide yields for these six packings were no larger than the averages for the 14 best-selling cigarettes.

TEST METHODS FOR QUANTIFYING THE PROPENSITY OF CIGARETTES TO IGNITE SOFT FURNISHINGS

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ABSTRACT

Research funded under the Fire Safe Cigarette Act of 1990 (P.L. 101-352) has led to the development of two test methods for measuring the ignition propensity of cigarettes. The Mock-Up Ignition Test Method uses substrates physically similar to upholstered furniture and mattresses: a layer of fabric over padding. The measure of cigarette performance is ignition or non-ignition of the substrate. The Cigarette Extinction Test Method replaces the fabric/padding assembly with multiple layers of common filter paper. The measure of performance is full-length burning or self-extinguishment of the cigarette. Routine measurement of the relative ignition propensity of cigarettes is feasible using either of the two methods. Improved cigarette performance under both methods has been linked with reduced real-world ignition behavior; and it is reasonable to assume that this, in turn, implies a significant real-world benefit. Both methods have been subjected to interlaboratory study. The resulting reproducibilities were comparable to each other and comparable to those in other fire test methods currently being used to regulate materials which may be involved in unwanted fires. Using the two methods, some current commercial cigarettes are shown to have reduced ignition propensities relative to the current best-selling cigarettes.

Key words: Fire, cigarettes, cigarette test method, ignition, upholstered furniture, statistical analysis

I. INTRODUCTION

A. Perspective on the Current Projects

Cigarette ignition of soft furnishings (upholstered furniture and mattresses) continues to be the leading cause of fire deaths in the United States.[1] In 1990, the nation experienced 1220 lost lives, 3358 serious civilian injuries, and $400 million in direct property loss from 44,000 cigarette-initiated fires in structures. These figures continue a slow downward trend (except in property loss, which is increasing) with cause(s) suggested but not established.

As a means to accelerate reducing these losses, the Cigarette Safety Act of 1984 (Public Law 98-567) created a Technical Study Group on Cigarette and Little Cigar Fire Safety (hereafter, TSG) and directed it to:

> "undertake such studies and other activities as it considers necessary and appropriate to determine the technical and commercial feasibility, economic impact, and other consequences of developing cigarettes and little cigars that will have a minimum propensity to ignite upholstered furniture or mattresses."

In its final report [2], the TSG concluded that:

> "It is technically feasible and may be commercially feasible to develop cigarettes that will have a significantly reduced propensity to ignite upholstered furniture or mattresses."

However, in assessing the commercial feasibility, the TSG membership also noted that:

> "A valid and reliable test method is needed to measure the reduced ignition propensity of improved cigarettes."
>
> "... the current mockup method is usable for research measurements of the relative ignition propensity of cigarettes. However, because of the lot-to-lot variability of the fabrics and paddings used, this method should not be used as the standard test method."
>
> "None of the several alternative candidate test methods for measuring the cigarette ignition propensity of soft furnishings was usable in its current state of development."

These statements reaffirm what has been found for many products: desired performance must be *measurable*. This quality allows a specifier to declare what is expected of the product, the manufacturer to produce a desired commodity, and the vendor to demonstrate compliance with the specifier's demands. A standardized performance measurement or test method makes this possible. It then becomes the role of society to determine the level of performance it desires and how much it is willing to pay. It is noteworthy that several state legislatures have delayed mandating less fire-prone cigarettes for lack of a quantitative test method.

Recognizing this as a key link to reducing fire losses, the Congress enacted the Fire Safe Cigarette Act of 1990 (P.L. 101-352), noting that:

> "It is appropriate for the Congress to require by law the completion of the research described in the final report of the Technical Study Group on Cigarette and Little Cigar Fire Safety and an assessment of the practicability of developing a performance standard to reduce cigarette ignition propensity, and
>
> it is appropriate for the Consumer Product Safety Commission to utilize its expertise to complete the recommendations for further work and report to Congress in a timely fashion."

Accordingly, the Act directed that the National Institute of Standards and Technology's Center for Fire Research [now the Building and Fire Research Laboratory (BFRL)], at the request of the Consumer Product Safety Commission (CPSC):

> "(1) develop a standard test method to determine cigarette ignition propensity,
>
> (2) compile performance data for cigarettes using the standard test method developed under paragraph (1), and
>
> (3) conduct laboratory studies on and computer modeling of ignition physics to develop valid, user-friendly predictive capability."

This publication describes the research performed and the results obtained in responding to the first two tasks. NIST has developed two test methods with sound links to the real-world fire scenarios of concern. These methods were shown to be of useful reproducibility in a nine-laboratory evaluation. The methods were then used to evaluate a sampling of the most popular current commercial cigarettes, as well as some whose physical properties suggest they might show reduced ignition propensity. The completion of the third task is described in a companion report.

B. General Considerations Regarding Test Methods

There are several ways of describing test methods and the features that are necessary for their use in professional fire safety practice. The following sections describe these in the context of the current program.

1. Applications

The test methods developed here are intended to fulfill two potential roles. The first role is to serve as a *practical* basis for a possible performance standard. As stated earlier, a regulation presupposes the existence of a practical test method. It is not feasible to make cigarette ignition propensity assessments on a recurring basis by testing each cigarette type on all soft furnishings in the commercial marketplace because:

- The upholstered furniture market is extremely diverse and not well-defined in terms of the materials used and their market shares.
- Usage may cause soft furnishings to respond differently to contact with lighted cigarettes, perhaps as a consequence of such factors as fabric wear, the use of cleaning fluids, or alkali metal accumulation.
- The resources needed for such an approach would be prohibitive.

A second role for an ignition propensity test method is to assist the cigarette industry in meeting the goals of any such regulation. This has two potential applications:

- Guidance in product development, in which the test results are used to indicate progress toward more desirable ignition behavior; and
- Quality assurance on the production line, in which sample cigarettes taken at intervals are checked to ensure they meet the regulatory requirement.

2. Output

The output of a test method can be continuous, discrete, or pass/fail. In this order, the methods produce a decreasing amount of information to the regulator, product developer, and performance monitor. An example of the first is automobile gas mileage testing, where any value of miles per gallon may result from the dynamometer test measurements. The regulator then selects a value from the continuum as the acceptable product characterization. In test methods with discrete output, only a fixed number of results are possible. An example might be marksman ratings, which are based on the number of "hits" from a selected number of shots fired. Another example is tire traction ratings which place all results in a small number of categories. In each of these two examples, one obtains qualitative information about the performance of the product, relative to both the scale for evaluation and to other products. By contrast, a pass/fail test *only* provides an indicator of acceptability. For example, if you cannot read the eye chart correctly, you won't qualify for a driving license.

It is possible for a single type of test apparatus to be used in multiple modes. Consider the upholstered furniture mock-up experiments performed under the TSG program [3]. One could perform 10 ignition tests for a given cigarette on each of 3 mock-up constructions. A possible *continuous* output could be the mean time for ignition to occur, taking into account those tests that did not result in ignition. A *discrete* measure could be the number of tests that led to ignition. A *pass/fail* use might dictate that no cigarette burn longer than 1 minute on the mock-up.

As can be seen from the above examples, all of these types of methods are acceptable in everyday usage. However, it is preferable *but not mandatory* for product regulation that a test method provide a graded measure of performance. In this context it then becomes important to quantify the level of precision warranted by the measurements. This includes both the degree to which a single tester will reproduce the same result in multiple tests (repeatability) and the range of results that would be obtained when different testers perform the procedure (reproducibility). This will be discussed further in a later section.

3. Figure of Merit

Test methods may also be grouped by what it is that they measure. A *design* or *property* test measures a physical or chemical feature of the product. Thus, utilizing such a test method one might (improperly) extrapolate the results of the TSG study [2] and require that all cigarettes should be fabricated of tobacco below a prescribed packing density, be of less than a prescribed circumference, and be fabricated using paper of air permeability below a prescribed value. Alternatively, an index could be prescribed combining these factors. This kind of test presumes that the other descriptors of the product do not affect the desired performance. The result of a prescriptive regulation based on a property test is a (partial) description of the product.

By contrast, a *performance* test simulates the conditions of the (undesirable) outcome of the product's use. The TSG furniture mock-up testing is a convenient example. A regulation based on this kind of test would not directly dictate the physical nature of the cigarette. However, it might impose subtle limitations. For example, a 5 cm x 5 cm mock-up surface could not support a 15 cm long cigarette while exposing the fabric to the coal. Very long cigarettes would thus be discriminated against by the method, possibly restricting their introduction into the marketplace.

The degree to which a performance test replicates the potential hazard leads to further considerations. Ideally, the test should mimic the actual cigarette-initiated fire conditions as closely as possible. Since the critical elements of these conditions are simply the cigarette and its immediate environs, this would seem to be readily achievable. One need only abstract the region of the upholstered chair, sofa or mattress that influences the ignition process and incorporate it in the test, effectively achieving a full-scale simulation of the real-world hazard. In practice, these environs are not unchanging; they may vary appreciably with furniture design and materials, as well as with the chance aspects of cigarette contact. Thus one or more realistic examples are chosen, an approach embodied in the use of upholstery mock-ups. A test consists of placing a lit cigarette on some small-scale configuration of a cushion covered by an upholstery fabric and observing the consequences. If a smolder zone develops in the fabric and spreads continually away from the cigarette coal, the cigarette has failed the test. Successful tests such as this incorporate most of the relevant physics and chemistry, while not necessarily replicating the real world hazard exactly.

The other general orientation which a performance test method could take is to measure some aspect of the cigarette which has been shown to correlate with its tendency to ignite upholstered furniture. Such correlating features of the cigarette are not readily discerned. It is certainly useful to have some insights into the physics of the ignition process in order to pursue this approach. Ihrig *et al.* [4] examined a large number of upholstery fabrics and a small number of cigarettes. They inferred that only the total radiative heat output of a cigarette (joules/cig.) was a useful predictor of ignition propensity. Gann *et al.* [3] examined a wide variety of experimental cigarettes as part of a detailed study of the physics of the ignition process, but found no single *performance* parameter which gave a strong correlation with ignition propensity. The current study has been more successful in finding a performance measurement that correlates with ignition propensity, as described below.

4. Validity

The results of a performance test method must be linked to the real world; *e.g.*, for cigarette testing, there must be a direct correlation between the test method outcome and the real-world propensity to cause cigarette ignitions. As is often the case, this is a difficult matter here, because the actual condition (and thus ignition susceptibility) of in-use upholstered furniture cannot be well characterized.

For nearly all fire tests, the needed degree of reality is demonstrated by physical similarity between the test method and the real-world hazard and/or by use of the physical principles that determine fire initiation and growth. The principal basis for relating mock-up and full-scale behavior of furniture ignition by cigarettes is reported in reference 3. That study, while necessarily limited in the range of materials, chair configurations and number of test replicates, nevertheless established that:

- upholstery mock-ups can differentiate among cigarettes, and
- mock-up ignition behavior has shown a statistically-significant correlation with the behavior of full-scale chairs containing the same fabric and padding in the TSG study [2].

Evidence is presented in Section II.B that the substrates chosen for the Mock-Up Ignition Test Method are appropriate to represent actual upholstered furniture. The similarity of the two methods (with their different performance measures) in rating the performance of both experimental and commercial cigarettes (Section IV) lends credence to the validity of both.

5. Long-Term Utility

While the previous study revealed a set of mock-up material combinations capable of differentiating among cigarettes, it did not provide the necessary assurance of long-term test method reproducibility. The upholstery materials used there and, in fact, upholstery materials in general are not subject to any kind of quality control which bears on their ignitability by cigarettes. On the contrary, there have been indications that even a fabric such as California Standard cotton velvet [5], long used to assess the cigarette ignition resistance of flexible cushioning materials, has been inconsistent in its behavior [3]. One of the significant concerns of the present study has been to assess the factors which need to be controlled to assure long term consistency in mock-up response to cigarettes. The result of this work is a "Mock-Up Ignition Test Method" in which the substrates consist of cotton duck fabrics and a polyurethane foam. The details of the work which led to this method are presented in Section II.B.

To reduce further the dependence on substrate materials whose properties may be hard to assure on a long-term basis, a substantial effort has also been invested in developing a second test method. This "Cigarette Extinction Test Method" uses standard cellulosic filter paper as the sole material in contact with the tested cigarette. This method determines whether a selected number of layers of filter paper absorbs enough heat from the cigarette coal to extinguish the cigarette. Reproducibility of test materials is gained at the cost of evident physical similarity to the real-world fire scenario. Thus, a correlation with upholstery ignition measurements, as in Section IV, is necessary to establish the method's validity. A detailed description of this method is given in Section II.C.

II. TEST METHODS DEVELOPED IN THE PRESENT STUDY

A. Cigarettes Used in the Present Study

1. Series 100 Experimental Cigarettes

Series 100 refers to the series of cigarettes whose ignition propensities were measured in the previous study [3] (referred to throughout this report as the TSG study). They thus enable connecting the test methods developed in this study with the prior results. The 32 cigarettes were manufactured by the cigarette industry with then-current hardware at slower speeds. They varied systematically in five parameters at two levels, reported to be at the extremes of that equipment, with all other properties stated by the manufacturers to be identical, but not specified. The variable parameters and their values were:

- tobacco blend (Burley or flue-cured),
- tobacco expansion (nonexpanded, 60 cuts/inch; or expanded, 30 cuts/inch),
- cigarette circumference (nominally 21 or 25 mm),
- cigarette paper permeability (nominally 10 or 75 CORESTA units), and
- cigarette paper treatment (untreated or treated with approximately 0.8% sodium potassium citrate).

It should be noted that these experimental cigarettes may differ substantially from current commercial practice in having limiting values of some design parameters and in having no specification at all for other potentially pertinent parameters such as humectant or flavoring additive levels.

Table 1 gives the experimental cigarette designations with respect to the five parameters and the assigned cigarette numbers. Detailed information on the cigarettes can be found in the tables and appendices of Section 2 of reference 3, 3. Table 2 gives the ignition behavior of the TSG cigarettes summed over the four mock-up configurations used there.

The Series 100 cigarettes have been kept in cold storage (approximately -18 °C) since the end of the TSG study in 1987. Because approximately 4 years had elapsed between the two studies, changes in the cigarettes were possible. NIST thus undertook a reevaluation of the ignition propensity of the cigarettes on the same fabrics and padding materials used in the original TSG study. These had been stored in a nominally climate-controlled room ($\approx$ 21 °C, 30-60 % R.H.) since the end of the TSG study. There was not enough of the original batch of the California Standard cotton velvet to allow reevaluation of all 32 Series 100 cigarettes, so a subset of eight was chosen representing (a) ignition propensities that evenly spanned the entire range of ignition rates and (b) a distribution of values of each of the five design factors listed above. Those chosen were numbers 101, 103, 106, 108, 120, 129, 130, and 131.

Details of the results of the reevaluation can be found in [6], which has been included as Appendix A to this report. For three of the substrates, the data are consistent with the hypothesis of no change in the ignition properties of the cigarettes. However, there were some increases in ignition for cigarettes 101, 103, 129, and 130, with most being on the denim substrate. In the original evaluation, these four cigarettes tended to self-extinguish on the denim mockup, whereas in the reevaluation, mock-up ignitions tended to occur. The initial suggestion was that the change was due to deterioration of the denim fabric. However, Lorillard performed measurements of smolder proclivity using their published method [4], as well as weight, density and air permeability on the denim fabric, and determined that those properties had not changed with storage.

This result prompted a closer investigation of the two sets of ignition experiments. Three main differences were noted in the test methods:

- The original lab was not available for use in the reevaluation, so another test lab was used. The canopy hood in this lab had a slightly lower draw. This was not thought to be a serious problem because the smoke was being carried from the test chambers in a manner similar to the original study.

- A technician with no previous experience in ignition testing conducted the reevaluation tests. As a check, re-tests of cigarettes 101, 103, and 130 on the denim substrate were performed by the same operator who had performed the original TSG evaluation. The same tendency for more ignitions was noted.

- The original evaluation of the denim mockup was done in August, when the relative humidity in the test lab was 50 to 60 percent. The reevaluation was done in January and February, when the relative humidity was 30 to 40 percent. Other data indicate that a decrease this large can increase the number of ignitions. This suggests that the differences seen with certain cigarettes (101, 130) might be caused by this parameter. This particular substrate would be expected to be more sensitive to ambient humidity than the others in the TSG study since it virtually surrounds the cigarette with cellulosic materials--two cushions which form a crevice plus a cover fabric.

Table 1. Description of Series 100 Experimental Cigarettes

Experimental Designation	Packing Description				
	Tobacco Blend	Packing density	Paper Porosity	Paper Additive	Circum. (mm)
101 BNLC-21	Burley	Non-Expanded	Low	Citrate	21
102 BNLN-21	Burley	Non-Expanded	Low	No Citrate	21
103 BNHC-21	Burley	Non-Expanded	High	Citrate	21
104 BNHN-21	Burley	Non-Expanded	High	No Citrate	21
105 BELC-21	Burley	Expanded	Low	Citrate	21
106 BELN-21	Burley	Expanded	Low	No Citrate	21
107 BEHC-21	Burley	Expanded	High	Citrate	21
108 BEHN-21	Burley	Expanded	High	No Citrate	21
109 FNLC-21	Flue-Cured	Non-Expanded	Low	Citrate	21
110 FNLN-21	Flue-Cured	Non-Expanded	Low	No Citrate	21
111 FNHC-21	Flue-Cured	Non-Expanded	High	Citrate	21
112 FNHN-21	Flue-Cured	Non-Expanded	High	No Citrate	21
113 FELC-21	Flue-Cured	Expanded	Low	Citrate	21
114 FELN-21	Flue-Cured	Expanded	Low	No Citrate	21
115 FEHC-21	Flue-Cured	Expanded	High	Citrate	21
116 FEHN-21	Flue-Cured	Expanded	High	No Citrate	21
117 BNLC-25	Burley	Non-Expanded	Low	Citrate	25
118 BNLN-25	Burley	Non-Expanded	Low	No Citrate	25
119 BNHC-25	Burley	Non-Expanded	High	Citrate	25
120 BNHN-25	Burley	Non-Expanded	High	No Citrate	25
121 BELC-25	Burley	Expanded	Low	Citrate	25
122 BELN-25	Burley	Expanded	Low	No Citrate	25
123 BEHC-25	Burley	Expanded	High	Citrate	25
124 BEHN-25	Burley	Expanded	High	No Citrate	25
125 FNLC-25	Flue-Cured	Non-Expanded	Low	Citrate	25
126 FNLN-25	Flue-Cured	Non-Expanded	Low	No Citrate	25
127 FNHC-25	Flue-Cured	Non-Expanded	Low	Citrate	25
128 FNHN-25	Flue-Cured	Non-Expanded	High	No Citrate	25
129 FELC-25	Flue-Cured	Expanded	Low	Citrate	25
130 FELN-25	Flue-Cured	Expanded	Low	No Citrate	25
131 FEHC-25	Flue-Cured	Expanded	High	Citrate	25
132 FEHN-25	Flue-Cured	Expanded	High	No Citrate	25

Table 2. Ignition Propensity of Series 100 Experimental Cigarettes [3]

Cigarette Designation	Number of Ignitions in 20 Tests	Fraction of Ignitions
101	13	0.65
102	12	0.60
103	17	0.85
104	19	0.95
105	6	0.30
106	1	0.05
107	11	0.55
108	7	0.35
109	15	0.75
110	16	0.80
111	19	0.95
112	20	1.00
113	6	0.30
114	4	0.20
115	14	0.70
116	12	0.60
117	18	0.90
118	18	0.90
119	20	1.00
120	20	1.00
121	14	0.70
122	7	0.35
123	15	0.75
124	15	0.75
125	18	0.90
126	17	0.85
127	20	1.00
128	20	1.00
129	10	0.50
130	4	0.20
131	15	0.75
132	12	0.60

2. Series 500 Experimental Cigarettes

The remaining supply of several of the TSG cigarettes was insufficient for use throughout the present study, especially in the round robins. This led NIST to request from the cigarette industry a new lot of experimental cigarettes. Since the Series 100 cigarettes had shown a near-continuum of ignition propensities, the new Series 500 cigarettes were to be comparable in the five properties described earlier. Approximately 10,000 of each were supplied by the industry and placed in freezers until conditioned for test usage.

Since the need for the current project was specimens with a breadth of ignition propensities, **it was not necessary to assume, nor was it assumed, that the counterpart cigarettes would be identical.** Only a modest effort was made to characterize the new samples. A random selection of eight cigarette types to be used in the test method development was conditioned at 55 ± 5 % RH. Forty of each were weighed and the mean and standard deviation were determined. These weights and standard deviations for both series are shown in Table 3. Table 4 shows the weight and standard deviations provided by the cigarette industry for the Series 100 and 500 cigarettes. It should be noted that there are some significant differences in (a) cigarette weights between the two series in each table, (b) the weights in the two tables, and (c) the standard deviations in the two tables. The sources of these differences are not known.

Table 3. NIST Comparison of Series 100 and 500 Cigarette Weights

Cigarette Identity	Weight (mg)	Std. Dev. (mg)
101	831	14
501	826	19
103	835	36
503	824	17
106	640	9
506	592	17
108	565	40
508	588	15
120	1090	42
520	1065	27
129	836	47
529	845	32
130	841	7
530	842	30
131	959	22
531	844	22

The same eight cigarette types were also tested to ascertain that they would demonstrate a range of ignition performance and to gauge how useful the TSG data would be in estimating their performance. The cotton duck/polyurethane foam mock-ups were the same as those described below for use in the Mock-Up Ignition Test Method, and 24 replicates were performed on each. The new and old ignition data are shown in Table 5. Clearly, the cigarette/substrate combinations do show a range of ignition propensities suitable for intra- and interlaboratory evaluation of the methods being developed. There is a general similarity of the two data sets, although they do not correlate exactly. It was not determined whether the differences were due to variations in the cigarettes, materials, apparatus, or laboratory conditions. It should be noted that variations between the two limited data sets are essentially within the reproducibility of the Mock-Up Ignition Test Method assessed in this report (see below).

Table 4. Cigarette Industry Comparison of Series 100 and 500 Cigarette Weights

Cigarette Identity	Weight (mg)	Std. Dev. (mg)
101	873	5
501	840	3
103	882	10
503	841	0
106	613	5
506	615	3
108	612	5
508	612	6
120	1131	6
520	1104	1
129	846	5
529	853	3
130	862	4
530	849	2
131	936	1
531	855	4

Table 5. Comparison of Ignition Propensities for Series 100 and 500 Cigarettes

Series 100 Cigarettes			Series 500 Cigarettes		
TSG Cig. No.	Number of Ignitions	% Ignitions	TAG Cig. No.	Number of Ignitions	% Ignitions
106	1/20	5	506	9/72	13
130	4/20	20	530	0/72	0
108	7/20	35	508	24/72	33
129	10/20	50	529	12/72	17
101	13/20	65	501	70/72	97
131	15/20	75	531	47/72	65
103	17/20	85	503	71/72	99
120	20/20	100	520	72/72	100

B. Mock-Up Ignition Test Method

This section begins with a brief review of the past use of upholstered furniture mock-ups. It continues with a detailed discussion of the individual factors considered in the final design of this test method, which uses mock-ups to measure ignition propensity of cigarettes. The method itself is delineated in Appendix B.

1. Previous Use of Mock-Ups

As noted above, an upholstery mock-up is a reproduction of the upholstered furniture ignition problem. This has led to the widespread use of mock-ups in conjunction with the assessment of the vulnerability of upholstery materials to cigarette ignition. Much of this work is reviewed in reference [7]. Essentially all of the early work in this area was focused on the assessment of the cigarette ignitability of upholstery materials with a particular emphasis on fabrics. One standard test method for upholstered furniture ignition, NFPA 260, for example, uses a single cigarette type and a single type of polyurethane foam to test fabrics and divide them into classes dependent on the extent of smolder spread away from the cigarette coal [8].

More recently, the cigarette type has been varied to discern the extent to which its parameters affect mock-up ignition. Ihrig *et al.* [4], tested four cigarettes on mock-ups constructed from 33 commercial cellulosic upholstery fabrics of varied weight and construction; the underlying cushioning material was either cotton batting or a single polyurethane foam. The mock-up configurations included flat, 90° crevice and 20° crevice (a crevice configuration involves two separate foam-covered cushions brought together at the angle indicated). The principal cigarette variables were circumference and tobacco packing density. From a statistical analysis of their results, the authors concluded that the fabric variables (alkali metal ion content, weight and density) dominated the behavior of the ignition process; only the total radiative heat output of the cigarette had a significant impact of the likelihood of ignition. They also found that fabrics gave a graded ignition response (*i.e.*, other than 0% or 100% ignitions) only over a rather narrow range of properties.

In a subsequent study, Ihrig *et al.* [9] studied separately the impact of varying the characteristics of the polyurethane foam. Here only two cigarettes and three fabrics were used, and all results were for the 90° or 20° crevice mock-up configurations. The principal foam variable influencing mock-up ignitability was found to be air permeability. It is probable that the sensitivity to this parameter is greater in the crevice configurations used than it is in a flat mock-up. Once again, the sensitivity of the ignition behavior of the system was inferred to be greater for a mock-up variable (foam air permeability) than for the cigarette variable examined (radiative heat output per cigarette).

The potential impact of cigarette modifications on the ignition of upholstered furniture mock-ups may be underestimated in these studies in that the cigarette designs were not varied as much as those in the TSG study [3]. However, these studies do illustrate the point that the ignition or non-ignition of a mock-up is dependent on both the cigarette design and the mock-up materials. Rhyne and Spears [10] applied this point to actual furniture using the model developed in Ref. 9 and various assumptions about the distributions of fabric and foam materials in the real world.

As will be seen below, variation in the properties of the fabric used in the mock-up provides a useful means of discrimination among cigarette ignition propensities.

2. Fabric Considerations for a Mock-Up Test Method

The previous work revealed some of the advantages, sensitivities and limitations of mock-up testing for research purposes. However, the present program is the first extensive effort to pursue a standard test method for cigarette ignition propensity. Thus, comparatively little attention has been given in previous work to the issue of the long-term reproducibility of the ignition behavior such mock-ups produce.

The principal focus in this study of mock-up systems capable of long-term reproducibility has been the consistency of the fabric. It is the fabric which most closely interacts with the cigarette and whose ignition (when the substrate is a polyurethane foam) sets the stage for all subsequent behavior of the mock-up. Both chemical and physical features of a fabric influence its smolder propensity.

It has long been known that the principal chemical feature affecting the smoldering ignition propensity of a cellulosic fabric is its content of alkali metal and alkaline earth cations [11]. Sodium and potassium ions are particularly prevalent in such fabrics [4]. Potassium ions, in particular, are present naturally in cotton; sodium ions appear to be commonly used in fabric dying processes. Both are also introduced from perspiration and soiling [3]. These metal ions are present in the fabric in the form of organic and/or inorganic salts. It has not been generally appreciated in the past that the *anion* associated with the metal cation has a substantial influence on the effectiveness of the metal in catalyzing fabric smoldering. Thus, in reference [4] the total sodium and potassium ion content in 33 fabrics was reported along with fabric ignition temperatures and yarn "smolder proclivity" (total time an individual yarn from a fabric smoldered); the correlation between these two measures of smolder propensity and the total metal ion content showed a lot of scatter, possibly because the metal ions were present in a variety of salts.

The smoldering ignition propensity of a fabric is also influenced by its physical characteristics; this is particularly true when the ignition source is a cigarette. The influence of contact with the mock-up surface on the cigarette coal was examined to a limited extent in this study. It was apparent that the heat loss into the fabric can temporarily slow or even completely stop the smoldering process in the cigarette coal; the magnitude of the disturbance depends on the cigarette design and on the thermal capacitance of the fabric. The fabric thickness, density, heat capacity and thermal conductivity all play a role in determining this effective thermal capacitance. Thus, fabric structure needs to be closely controlled in any standardized material to be used in mock-up testing.

Criteria Used to Identify Suitable Fabrics. Discussions with representatives of the fabric and furniture industries made it clear that there is no practical way to characterize quantitatively the relative popularity of the thousands of upholstery fabrics used in the soft furnishings at risk to fire. If sales records are kept by individual fabric manufacturers or their customers, they are not publicly available. Therefore, identifying a set of test fabrics representative of the real-world was not a feasible undertaking and alternative approaches were pursued.

The ideas in the preceding paragraphs were blended with other considerations to arrive at the following selection requirements for suitable test fabrics:

- susceptibility to ignition from smoldering cigarettes, making the likely candidate fabrics to be cotton, linen, modacrylic and acrylic;
- differentiation of the ignition propensities of various types of cigarettes;
- capability to provide reproducible test results;
- ready availability now and in the future, with essentially constant cigarette ignitability in successive batches.
- manufacture such that their chemical and physical properties can be reproduced (inter- and intra-bolt);
- consistency of surface characteristics, so that surface contact between the cigarette and fabric surface remains constant along the length of the cigarette tobacco column and across the length and width of the fabric bolt;
- no preference for smoldering ignition in one orientation (*i.e.*, warp or weft yarns), making fabrics with similar warp and weft yarn construction preferable;
- freedom from finishes (*e.g.*, for flame retardancy, durable-press, or crush resistance), since (a) perfectly even finish surface characteristics and adhesion are difficult to obtain in commercially produced fabrics and (b) some finishes may promote or prevent smoldering ignition of the fabric; and
- weight in range representative of fabrics that are commonly used in the commercial upholstery fabric marketplace (0.17-0.85 kg/m^2; 5-25 oz/yd^2). Fabrics below about 0.34 kg/m^2 (10 oz/yd^2) tend to wear rapidly; those above 0.85 kg/m^2 (25 oz/yd^2) are very difficult to shape to an article of furniture.)

Air permeability of the fabric was not one of the chosen criteria for three reasons: (1) this parameter was found to be relatively minor in the statistical model of Ihrig *et al.* [4]; (2) there is reason to believe that the oxygen coming through the fabric is a minor contributor to the oxygen needs of the cigarette coal; see Appendix C; (3) the primary means of oxygen permeation through the fabric is believed to be diffusive, whereas air permeability measurements are based on air flow resistance.

The levels of cations in the fabric were also not included in the criteria. The original intention was to control this level by doping to a cation level which assured sustained smolder propagation; the cotton ducks that were ultimately used have such a cation level in their as-received state (see below).

To survey for appropriate fabric criteria and potential fabrics for use in a cigarette test method, NIST consulted with:

- research and test labs (California Bureau of Home Furnishings and Thermal Insulation, Department of Defense - Natick Textile Research Labs, Consumer Product Safety Commission),
- textile and furniture trade associations (American Textile Manufacturers Institute, American Furniture Manufacturers Association),
- textile mills (Glen Raven Mills, Mt. Vernon Mills, Graniteville Mills, J.B. Martin, and West Point Pepperell, Inc.),
- a textile distributor (Douglas, Inc.),
- NIST test method development staff, and
- a company which supplies standardized fabrics (Test Fabrics, Inc.).

Each of these parties has experience with either developing flammability test methods/standards or standardized fabrics or producing, using or distributing commercial fabrics. Each party was asked to list criteria important to developing a standardized fabric for test method use, describe problems associated with the production of standardized fabrics, and suggest possible fabric types for use in the test method anticipated here.

Cross-referencing the suggested practices and fabric types against the needed fabric characteristics noted above led NIST to the selection of cotton ducks as the candidate fabrics. These have a simple physical structure (plain weave) subject to control of weave details and air permeability, a long history of manufacture, conformance to a military specification [12], and at least limited usage as upholstery fabrics. They present a smooth surface to the cigarette coal, minimizing variations in heat transfer from the coal to the fabric. They are also made from a single component, raw cotton. Having no pile such as that in the fabric used for testing by the State of California ("California velvet"), they require no added finish to achieve a uniform physical appearance. These fabrics were thus judged to be excellent candidates for use in a mock-up method.

The physical properties of the 100% cotton fabrics examined in this study are summarized in Table 6; only a subset of these was ultimately utilized in the test method (Duck #4, #6 and #10). All were manufactured by West Point Pepperell Mills of West Point, Georgia (now known as Wellington Sears

Company)[1,2]. Since all are made from raw cotton (Texas, short staple) it is expected that their chemical composition is nominally similar. (The metal cation content was checked separately, as noted below.) The cotton was card cleaned using mechanical agitation only. No lubricants, surfactants or sizing were added to the cotton during the cleaning, carding, roving, spinning or the weaving processes. The yarns were made using open-end spinning frame technology. The fabrics are known as "greige" goods because they have no finishes or dyes.

Table 6. Specified Nominal Properties of Fabrics

FABRIC DESIGNATION	AREAL DENSITY	YARN COUNT (PER INCH)	YARN PLIES	AIR PERMEABILITY*
Duck No. 4 Style S/01400240	0.83 kg/m^2 (24.5 oz/yd^2)	31 x 24	4 x 4	5.1 - 10.2 x 10^{-3} m^3/s/m^2 (1 - 2 ft^3/min/ft^2)
Duck No. 6 Style S/01600230	0.72 kg/m^2 (21.2 oz/yd^2)	36 x 26	3 x 3	5.1 - 10.2 x 10^{-3} m^3/s/m^2 (1 - 2 ft^3/min/ft^2)
Duck No. 8	0.61 kg/m^2 (18 oz/yd^2)	34 x 27	3 x 3	5.1 - 10.2 x 10^{-3} m^3/s/m^2 (1 - 2 ft^3/min/ft^2)
Duck No. 10 Style S/01102020	0.50 kg/m^2 (14.7 oz/yd^2)	40 x 28	2 x 2	10.2 - 20.4 x 10^{-3} m^3/s/m^2 (2 - 4 ft^3/min/ft^2)
Duck No. 12	0.39 kg/m^2 (11.5 oz/yd^2)	46 x 35	2 x 2	20.4 - 30.6 x 10^{-3} m^3/s/m^2 (4 - 6 ft^3/min/ft^2)
Twill	0.52 kg/m^2 (15.3 oz/yd^2)	40 x 28	2 x 2	10.2 - 20.4 x 10^{-3} m^3/s/m^2 (2 - 4 ft^3/min/ft^2)

* Measured by Federal Method 5450 (contained in Federal Test Method Standard 191A, July 1978)

The chief differences in these fabrics should reside in their physical properties, since chemically they are raw cotton with comparable metal ion contents (see below). It is likely that the most important difference is the areal density, which varies by a factor of two. The potential heat sink effect to a cigarette coal thus varies by this same factor among these fabrics. The air permeabilities vary by a factor of three but, as will be seen, the mock-up configuration which was used is flat, and its ignitability should be relatively less sensitive to this parameter since more of the cigarette coal's periphery is exposed to ambient air. (Fabric permeability ranked fourth in order of importance as a controlling variable in the ignition of a flat mock-up in reference [4]. Fabric weight and total sodium/potassium ion content were the two dominant parameters.)

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[1] The fabrics can be purchased from Wellington Sears Company, 3202 34th Street, Valley, AL 36854; telephone no. (205) 768-1222.

[2] Certain products or manufacturers are identified in this report in order to provide sufficient definition of procedures, equipment, and materials. In no case does such identification imply endorsement by the National Institute of Standards and Technology nor is the item identified necessarily the most appropriate for the purpose.

In anticipation of the fabric ignitability behavior discussed below, it is worth pointing out here that the ease of ignition of the cotton ducks in Table 6 is the opposite of what one might expect from previous literature results. The review of previous work [7] notes that cigarette ignition resistance decreases with increasing fabric weight. As will be seen below, the observable behavior of the fabrics in Table 6 is opposite to this trend; the heavy ducks ignite less readily than the lighter ducks. A plausible explanation of this is as follows.

The observed behavior in both situations (previous literature and here) is not the ignition event itself, which occurs close in to the cigarette coal, but rather the *sustained smolder spread* away from the cigarette coal (if and only if this spread can occur). The previous literature, with the possible exception of one experimental cigarette used in reference 4, is all based on commercial cigarettes which qualify as strong local ignition sources. The coal combustion for these cigarettes is sufficiently robust to overcome the heat losses to essentially the whole spectrum of fabric weights used in upholstered furniture; that is, they provide a sufficient heat flux to the fabric to ignite it locally in essentially all cases. However, among the commercial fabrics on which the previous literature is based, the heavier fabrics have a lesser surface-to-volume ratio, which yields a lesser heat loss rate and a greater tendency to propagate smoldering once it is locally initiated. Thus, given a strong igniter such as a commercial cigarette, a population of varying fabrics (having diverse levels of areal density, metal cation content and weave structure) will show a tendency for the observable part of the cigarette ignition process to be enhanced by increased fabric weight. The areal density or fabric weight effect will be most pronounced for those fabrics whose other parameters (metal cation content or weave structure) tend to be marginal in sustaining smolder propagation.

Here, however, the focus is shifted more specifically to *whether* local smoldering ignition of the fabric occurs. The cigarettes used are not necessarily strong igniters, but the cotton duck fabrics will smolder readily if ignited. Many of the experimental cigarettes used here are so disturbed by the heat loss they experience when in contact with the fabric that they go out. Others survive, but the coal is weakened in the area of contact with the fabric. Thus, in this case the transient heat sink effects of the fabrics are paramount. Heavier fabrics are greater heat sinks and therefore more ignition resistant.

Additives as a Possible Means of Smoldering Ignitability Control. Because commercial fabrics can show significant lot-to-lot variability in chemical and physical parameters, a substantial effort was made in the present study to develop a set of controlled fabrics. The cotton ducks in Table 6 were the basis for this development. As noted above, the cotton ducks have the necessary physical property control. As a means to render them completely specifiable with regard to cigarette ignition propensity, controlled doping with alkali metal and alkaline earth salts was investigated.

Appropriate salts must provide unambiguous self-sustained smolder propagation in the fabric when present above some minimum level. Above this minimum, they must also yield a differential ignitability response in the fabric when exposed to experimental cigarettes having differing ignition propensities (as judged by their behavior in the TSG study, reference 3). In practice, this last requirement probably translates into an ignition temperature which is in just the right range for some (not all) cigarettes to be able to induce in a fabric and which decreases continually with increased salt concentration. At the beginning of this study the identity of a suitable metal salt was unknown; and, as noted above, the important role of the anion was not known either. A variety of salts suggested by the limited literature in this field was examined:

- potassium chloride,
- potassium acetate,
- calcium acetate,
- sodium bicarbonate,
- mixtures of sodium borate with boric acid,
- potassium acetate with boric acid, and
- potassium acetate with diammonium phosphate.

All of these potential additives eventually were rejected because none could produce cigarette differentiation when present in the cotton ducks at levels sufficient to assure evenly propagating, self-sustained smolder. Furthermore, a problem with locally nonuniform deposition of the salts in the cotton ducks compounded the difficulty of the search and was not completely solved. Laundering and acid-washing of the fabrics prior to salt treatment proved insufficient to assure uniform penetration by the aqueous salt solutions. Commercial scrubbing followed by doping with commercial padding equipment probably could have resolved these difficulties, which may have been caused by natural waxes in the cotton.

Interestingly, the salts naturally present in raw cotton show no evidence in their smolder behavior of local non-uniformity problems, and tests showed that the unaltered fabrics in Table 6 could provide cigarette differentiation. Consultation with personnel at the USDA Southern Regional Laboratory [13] together with information from a standard reference text [14] indicated that the dominant salt in raw cotton is potassium malate. This salt is not commercially available. Limited studies with small quantities produced in our laboratory indicated that it could yield cigarette differentiation behavior similar to that seen with the cotton ducks in their "as-received" states. The non-availability of this salt, coupled with the lack of commercially scrubbed fabrics as hosts (even in small-scale laboratory studies) led to the termination of this approach to test fabric production.

Since the cotton ducks possessed all the desired properties of a controlled fabric for a mock-up based test method, including the desired cigarette differentiation in their as-received state, further development was pursued with these as-received cotton ducks as the fabrics of choice. Given this, it was necessary to assure that they could continue to meet the necessary criteria as to availability and invariant ignitability.

Continued Availability of Cotton Duck Fabrics. The simple plain or basket weave construction and desirable properties (high abrasion resistance, strong tear and tensile strengths) of cotton ducks make them highly sought-after products. For example, the U.S. Department of Defense has developed a number of specifications for cotton ducks which results in highly standardized fabrics. The military uses large quantities of these fabrics in products such as upholstery (camp seating slings), backpacks, tenting, sandbags, and medical stretchers. Commercially, cotton ducks are commonly used as an upholstery fabric in director's chair canvas slings. They have also been used in upholstered furniture, but this use is driven by home fashion trends. Currently they are featured as upholstery fabrics in a number of mail order and furniture periodicals [15].

As a result, these fabrics are produced in bountiful supply by textile companies throughout the world. In fact, cotton duck fabrics have been produced continuously for more than 200 years. There are approximately 34 million m^2 of cotton ducks (greater than 50% cotton content) sold annually in the United States. This information provides a high degree of assurance that cotton ducks will be readily available and produced in a consistent and standardized manner.

Metal Ion Content Over Time. Since cotton ducks are made from raw cotton, their content of alkali metal and alkaline earth ions is potentially variable with soil, fertilization and growth conditions. Blending of raw cotton from various regions (of Texas) and crop years tends to counteract this variability. Recognizing the potential problems here, NIST sought to develop information on the extent of variability of cation content in cotton ducks. This process was greatly simplified by determinations that:

- the alkali metal ions are comparable in smolder promotion tendency and much more potent than the alkaline earth cations [16] and
- potassium ions are present in dominant concentrations in the cotton ducks and the relative fractions of the other metal ions varied little (Table 7).

The premise adopted was that the potassium ion concentration is the determining chemical factor in ignition susceptibility of these fabrics. The malate anion is equally important in setting the general level of activity of the potassium. Since this is the dominant anion in cotton [13] it is expected to correlate with the potassium level, barring any major genetic modifications to future cotton strains.

NIST then worked with West Point Pepperell (WPP) to examine the long-term reproducibility of the potassium ion content of the ducks. WPP staff utilized the NIST sample extraction technique (Appendix D) and atomic absorption spectroscopy to analyze samples from their mill for potassium ion content over a period of 4 months. (A reorganization of the company prevented a longer analysis period.) The results are shown in Table 8. Each duck was sampled in three locations during one day of each month reported; the standard deviations shown are for these three measurements. There is only one case (Duck #6 in June, 1992) of highly variable results. Otherwise the spatial variability on a given day is ± 6% or less. The long-term variation tends to be greater but, except for the one case of Duck #6 (June, 1992), the variation is not very large. Duck #8 shows the greatest variation, a 23% increase from 4700 to 5800 ppm, from April to May, 1992.

Table 7. Cation Content of Fabrics Used in the Preliminary and Main Interlaboratory Studies

Duck Number-Bolt Number	[Cation] (ppm ± one Standard Deviation)			
	Na^+	K^+	Mg^{+2}	Ca^{+2}
4-46*	<20	4575±133	607±19	691±26
4-48*	<10	4243±37	582±6	683±5
4-50	<15	4477±75	567±12	607±56
4-52	<20	4546±125	566±29	575±44
4-54	<25	4528±55	558±5	569±21
4-56	<20	4510±44	564±3	564±16
6-65*	<20	5667±185	653±13	748±13
6-67*	<35	5900±107	656±12	727±25
6-69	<45	4573±257	573±19	575±37
6-71	<30	5742±102	633±19	690±37
6-73	<15	4439±143	578±14	650±11
10-57*	<50	4445±88	607±9	708±16
10-58	<60	4214±71	580±10	691±17
10-59*	<20	4422±94	605±14	698±22
10-61	<60	4224±111	590±12	665±3
10-63	<70	4069±162	575±19	663±33

* Used in preliminary interlaboratory study; otherwise used in main interlaboratory study

Table 8. Potassium Content of West Point Pepperell Cotton Ducks Over a Four Month Period

TIME	DUCK NO.	POTASSIUM LEVEL (ppm)
April, 1992	4	5200 ± 220
" "	6	5200 ± 260
" "	8	4700 ± 200
" "	10	5500 ±190
May, 1992	4	5400 ± 170
" "	6	5600 ± 80
" "	8	5800 ± 230
" "	10	6000 ± 200
June, 1992	4	5800 ± 270
" "	6	8200 ± 2200
" "	8	5600 ± 50
" "	10	5700 ± 35
July, 1992	4	6000 ± 170
" "	6	5500 ± 340
" "	8	5800 ± 250
" "	10	6000 ± 24

Effect of Ion Content Variation on Mock-Up Ignitability. Table 9 shows the results of limited testing (5 replicates, 3 cigarette types) using ducks #4, #6 and #10 from the analyzed lots described in Table 8. The ignition propensities are comparable despite the noted variations in the potassium ion content of the fabric. The widest variations in potassium content were not included in this testing.

Table 9. Sensitivity of Ignition Susceptibility to K^+ Content in Fabrics; 5 Replicates

Fabric	$[K^+]$ (ppm)	Percent Ignition for Cigarette		
		#506	#529	#503
Duck #4	5400	0	0	100
"	6000	0	0	100
Duck #6	6000	0	20	100
"	8200	0	0	100

Limited testing was also done on a #8 duck from another manufacturer, obtained through the American Textile Manufacturers Institute (ATMI). Analysis showed this fabric to contain ≈ 100 ppm of sodium, 3500-5100 ppm of potassium, 450 ppm of calcium, and 320 ppm of magnesium. This was compared to WPP duck #8, which Table 8 shows to contain 4700 to 5800 ppm of potassium. The other, less critical metals were not greatly different from those in the WPP duck (Table 7). Six TSG cigarettes of differing ignition propensity again showed comparable ignition propensities on the two ducks (Table 10). (Comparable, as used in this context, means that any differences in ignition propensity were below the typical levels of scatter seen in these tests; this issue is discussed more thoroughly in the context of the round robin studies below.)

Table 10. Ignition Susceptibility of Different #8 Cotton Duck Fabric Samples (Percent Ignition in Six Replicates)

Cigarette Number	WPP Duck	ATMI Duck
106	0	0
114	0	0
108	0	0
129	17	33
101	100	100
120	100	100

The cation content of all fabrics used in the interlaboratory testing described below was monitored along the length of the fabric bolts used by the method described in Appendix D. Depending on the bolt length, anywhere from 3 to 10 samples were taken along the length of a given bolt and analyzed for sodium, potassium, magnesium and calcium content. A summary of this cation content is shown in Table 7. The numbers are the average of the samples taken on each bolt of fabric (± one standard deviation). Appendix D contains the cation content for all the individual samples tested. The most variable fabric is duck #6, with potassium levels ranging from about 4400 ppm to 5700 ppm in the bolts used in the main interlaboratory study (described below in Sect. B.8). This is a substantial range (*ca.* 30% referred to the smaller number), but it did not result in any extraordinary variability in the interlaboratory results obtained with this duck. The implication thus is that variations in metal cation content comparable to those seen in Table 7 (which in turn are comparable to those seen over the four-month period shown in Table 8) are not detrimental to the reproducibility of the mock-up test method discussed below.

The potassium levels in Tables 7 and 8 may seem high compared to many (not all) of the 33 commercial fabrics analyzed in the work of Ihrig [4]. However, this misses the role of the anion in shifting the catalytic effectiveness of the cation. Unfortunately, anion measurements were not made in reference 4. Thus, the relation of those results to the present levels, in terms of ignitability enhancement, is unknown.

For the best long-term reproducibility it is preferable that the potassium ion levels not be in a domain where the ignition behavior is sensitive to small changes in potassium level. The above results indicate that the potassium levels in the cotton ducks are indeed well above the sensitive region. The sensitive region for potassium acetate, noted in cigarette industry studies, was *ca.* 2000 ppm.

Physical Variability of Cotton Duck Fabrics. Areal density is believed to be the most important physical property affecting ignition susceptibility of the cotton ducks. The variability of this property along the length of the fabric bolts used in the interlaboratory studies described below is indicated in Table 11. The standard deviations and coefficients of variation are based on five samples from along the length of each bolt.

Air permeability measurements performed in accord with ASTM Method D 737-75 [17] were made on samples from several of the same bolts by the United States Testing Company. Five samples from each bolt were measured; the results (± the standard deviation) are shown in Table 12. The test method, apparatus, and pressure drop were fundamentally the same as that used to set the nominal air permeability specifications in Table 6. This small degree of physical variability in the cotton ducks was further reinforcement of the appropriateness of these fabrics for use in the interlaboratory study.

Also shown in Table 12 are the measured air permeability values for the three principal fabrics used in the TSG study [3]. The large variability of the Splendor fabric is the result of one particular sample; a coefficient of variation closer to that of California Velvet typified the other three samples measured here. It is of interest to note that the TSG fabrics have permeabilities that are ten to twenty times higher than the cotton ducks used here. This will not preclude similar types of ignition behavior from being exhibited by the two groups of fabrics, as will be seen below.

Table 11. Measured Areal Densities of Fabrics Used In Interlaboratory Study

Duck Number-Bolt Number	Areal Density (g/m^2)	Coefficient of Variation (%)
4-48	820 ± 17	2.0
4-52	806 ± 25	3.1
4-56	803 ± 14	1.7
6-67	712 ± 9	1.3
6-71	705 ± 18	2.6
10-58	506 ± 18	3.5
10-63	496 ± 6	1.1

Table 12. Measured Air Permeability of Fabrics Used in Interlaboratory Study and in TSG Study

Duck Number-Bolt Number or Fabric Name	Air Permeability*	Coefficient of Variation (%)
4-52	$(8.89 \pm 0.15)\times10^{-3}$ $m^3/s/m^2$ (1.75 ± 0.03 $ft^3/min/ft^2$)	1.7
4-56	$(8.74 \pm 0.91)\times10^{-3}$ $m^3/s/m^2$ (1.72 ± 0.18 $ft^3/min/ft^2$)	10.5
6-67	$(5.54 \pm 0.25)\times10^{-3}$ $m^3/s/m^2$ (1.09 ± 0.05 $ft^3/min/ft^2$)	4.6
6-71	$(5.54 \pm 0.15)\times10^{-3}$ $m^3/s/m^2$ (1.09 ± 0.03 $ft^3/min/ft^2$)	2.8
10-58	$(10.72 \pm 0.71)\times10^{-3}$ $m^3/s/m^2$ (2.11 ± 0.14 $ft^3/min/ft^2$)	6.6
10-63	$(11.53 \pm 0.61)\times10^{-3}$ $m^3/s/m^2$ (2.27 ± 0.12 $ft^3/min/ft^2$)	5.3
Splendor	0.12 ± 0.04 $m^3/s/m^2$ (24.1 ± 7.7 $ft^3/min/ft^2$)	32.0
Blue Denim	$(6.81 \pm 0.30)\times10^{-2}$ $m^3/s/m^2$ (13.4 ± 0.6 $ft^3/min/ft^2$)	5.0
California Velvet	0.12 ± 0.01 $m^3/s/m^2$ (23.2 ± 2.5 $ft^3/min/ft^2$)	11.0

* Data obtained by United States Testing Company using ASTM D 737-75

3. Other Mock-Up Materials

Two other expendable materials are used in the mock-up method. The principal one is a polyurethane foam which is used to mimic the typical cushioning material in upholstered furniture. A second material is a polyethylene film used between the fabric and foam in one mock-up configuration for reasons explained below.

Polyurethane Foam. The polyurethane flexible foam used in these test method development studies had the same formulation as that used in the TSG study. The foam is based on a polyether polyol and TDI; the manufacturer's (Vitafoam, Inc., High Point N.C.) designation is 2048.[3] It has an indent flexural rating of approximately 21.8 kg (48 lbs) and a nominal density of 32 kg/m^3 (2.0 lb/ft^3). The nominal air permeability (ASTM D3574 [18]) is 2.0 x 10^{-3} m^3/s (4.25 ft^3/min). The foam is representative of foam products used in the residential furniture market.

The sensitivity of the cigarette ignition process to foam properties was examined by substituting another common upholstered furniture foam. This foam had a similar TDI/polyether formulation, but a nominal density of 24 kg/m^3 (1.5 lb/ft^3) and a nominal air permeability of 2.4 x 10^{-3} m^3/s (5.0 ft^3/min). Flat mockups were made with duck #8 and the two foams. TSG cigarettes nos. 108 (7/20 TSG ignitions), 129 (10/20 TSG ignitions), 102 and 116 (both 12/20 TSG ignitions) were tested on the mockups using six replicates per cigarette/mock-up condition. See Table 13.

Table 13. Sensitivity of Ignition Susceptibility to Foam Properties
(Percent Ignitions in Six Replicates)

Cigarette Number	Ignitions (Heavier Foam)	Ignitions (Lighter Foam)
108	50	33
129	50	17
102	100	100
116	100	100

Since the foam density variation in this experiment is substantially larger than would occur within any well-specified foam batch (± 5%) and since the effect here was small, it was concluded that the role of foam property variations (within nominally similar formulations) is minimal. It should be sufficient to specify the general formulation and nominal density.

From consulting with experts on polyurethane foams, it was determined that the greatest (± 5%) variation in foam density occurs vertically in a bun. The air permeability varies similarly; see Table 14. In the interlaboratory testing described below, the foam samples were varied randomly from top

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[3] The foam was obtained from TEDCO, 2335 W. Franklin Street, Baltimore MD 21223; telephone no. (410) 945-6158. TEDCO identifies this foam as style #2045.

to bottom of the bun. As will be seen, the impact on the inter- and intra-lab variability was at an acceptable level. This means that the density and permeability range typical of current foam manufacturing practice are an acceptably small source of scatter in mock-up ignition behavior.

Table 14. Measured Air Permeability of Polyurethane Foam By ASTM D 3574 (Average of 3 to 4 samples at each location.)

Foam Bun	Location	Air Permeability
A	Middle	$(1.83 \pm .02) \times 10^{-3}$ m^3/s $(3.89 \pm .04$ $ft^3/min)$
A	Top	$(2.00 \pm .03) \times 10^{-3}$ m^3/s $(4.24 \pm .06$ $ft^3/min)$
B	Middle	$(1.80 \pm .01) \times 10^{-3}$ m^3/s $(3.82 \pm .03$ $ft^3/min)$
B	Top	$(2.01 \pm .02) \times 10^{-3}$ m^3/s $(4.26 \pm .03$ $ft^3/min)$

Polyethylene Film. In one of the mock-up configurations ultimately included in the test method described below, a polyethylene film was placed between the fabric and foam as an additional heat sink to make the mock-up more ignition resistant. Inadvertently, different films were used in the preliminary and the main interlaboratory studies described below. Table 15 lists the properties of the two films.

Table 15. Properties of Polyethylene Films Used in Conjunction with Duck #4

Property	Poly-America, Inc. (Preliminary RR)	Warp Bros, Inc. (Main RR)
Thickness (mm)	0.15 ± .007	0.13 ± .005
Density (g/cm^3)	0.79	1.15
Areal Density (g/cm^2)	0.012	0.015
Melting Points (°C)*	118, 124	115, 122

* Two distinct peaks for crystalline regions were found for each polymer film.

As will be seen below in comparing the preliminary and main interlaboratory results, these property differences (most likely the areal density difference) were sufficient to yield differing ignition propensity measurements on two cigarettes in the interlaboratory studies. The film to be used in the test method is specified similar to the one manufactured by Warp Brothers, Inc. under the trade name Poly-Film; it was obtained from Read Plastics, Rockville, MD 20852. The reason for this preference emerges from the interlaboratory studies described below.

4. Mock-Up Configuration

Several issues were considered in deciding how the mock-up assemblies were to be configured. These affect the degree of replication of the real-world situation, ease of fabrication, and reproducibility of test results.

The first issue concerns fabric/foam contact. Wrapping the fabric around the foam (totally or partially), as done in earlier studies, makes it difficult for the test operator to obtain reproducible, even and constant tension of the fabric over the foam. The resulting variation in surface contact between the fabric and foam changes the local thermal capacitance of the mock-up, which in turn affects its susceptibility to ignition. This is especially important for the cotton ducks, which are extremely flat and maintain very good surface contact with the foam in a flat configuration, but for which side wrapping of the fabric around the foam would produce a significant surface contact problem.

A second issue concerns whether the mock-up should mimic a crevice or a flat area of upholstered furniture. The greatest realism would doubtless come in some degree of crevice configuration. However, the crevice design introduces reproducibility problems. Accurate placement of the two cushions to form the crevice is important so that the intersection line is even and repeatable. This difficulty is compounded by the sensitivity of a cigarette's ignition propensity to its placement relative to both surfaces. Tests at CSIRO in Australia have indicated that the outcome of a crevice test (ignition or nonignition) can be heavily influenced by how firmly the operator places the cigarette in the crevice [19]. This introduces a potentially strong operator dependence that is undesirable.

Third is the desired degree of ignition susceptibility of the particular mock-up to the heat produced by the cigarette. In the TSG full-scale furniture tests [3, 3], the commercial cigarette, a strong igniter, generally showed a higher fraction of ignitions in the crevice configuration. Apparently the cigarette coal generated enough heat to overcome the high thermal capacity of two fabric surfaces and the restricted oxygen flow to the combustion zone. The four experimental cigarettes, with lower bench-scale ignition propensities and presumably lower heat transferred, showed no consistent trend between crevice and flat configurations. Various crevice substrates in the full-scale chairs produced higher, similar or lower fractions of ignitions than the flat systems comprised of the same fabric and padding. These results suggest that the flat configuration might better differentiate among cigarettes of high ignition propensity than the crevice; on the other hand, Ihrig *et al.* [4], using four cigarettes on thirty fabrics, found the crevice to discriminate among their cigarettes while a flat mock-up did not. For the cotton ducks used in this study, limited experiments were performed to see if a crevice mock-up would aid in discriminating among the high ignition propensity cigarettes. The crevice mock-up was found to be more ignitable and thus not helpful in seeking the desired discrimination. For cigarettes of lower ignition propensity, there is no clear advantage of either configuration.

A fourth consideration is the surface size of the mock-up. This should be large enough to accommodate any reasonable length cigarette, while being small for ease of maintaining uniformity of contact between the fabric and the lower layer(s) of the substrate.

For these reasons, it was decided to test in only the flat configuration. In addition, a square, flat brass frame (20 cm outer edge, 2.54 cm wide) was developed for placement on top of the fabric to assure that it remained in excellent contact with the foam below. The use of the frame is distinctly more reproducible than anchoring the fabric edges with pins. The frame also guarantees that the cigarette is placed in the same mockup location from test to test. The hot cigarette coal is placed in the center of the mockup and the non-ignited tip (filter) of the cigarette is oriented toward one of the right-angled corners of the frame.

The mockup was enlarged, compared to the mockups used in the TSG study, to 20.3 cm x 20.3 cm (8" x 8"). This provides an ample-sized mockup for almost any cigarette length and eliminates the need to determine the warp or weft orientation of the fabric with respect to mockup orientation. Placing the cigarette on the mockup at a 45° angle assures that the smoldering cigarette tobacco column will make equal contact with the warp and weft yarns of the fabric.

With this flat configuration, consisting simply of a square of cotton duck held in good contact atop a square of polyurethane foam (5.1 cm thick), a series of screening tests was performed to determine the degree of ignition propensity differentiation provided by the various fabrics. Table 16 summarizes the results.

**Table 16. Percent Ignitions on Various Substrates for Selected Cigarettes
Flat Configuration; 4 to 6 Replicates**

Fabric → Cigarette # and TSG Ignitions ↓	Duck #6	Duck #8	Duck #10	Duck #12
106 (1/20)	0	0	33	67
114 (4/20)	0	0	33	67
113 (6/20)	0	0	50	100
108 (7/20)	17	0	50	100
129 (10/20)	25	50	67	100
101 (13/20)	100	100	100	100
120 (20/20)	100	100	100	100

Table 16 shows that these fabric/foam mock-ups do provide varying degrees of differentiation of the cigarettes. Ducks #6 and #8 were similar to each other. Duck #10 was more readily ignited. Duck #12 (and the twill fabric in Table 6) provided only minimal differentiation among the weakest igniting cigarettes. Duck #4, when assessed with a different set of TSG cigarettes (114, 108, 107, 101, 124, and 125), showed a transition from non-ignition to ignition not greatly different from that of Duck #6.

It was also desirable to have at least one mock-up which would be resistant to all but the most ignition prone cigarettes (*e.g.*, TSG rankings of 15/20 through 20/20). It is well known that polyester battings used in upholstered furniture act as a heat sink and absorb the energy from a smoldering cigarette. This suggested the use of a similar concept, the use of a thin, high density heat sink material in better thermal contact with the fabric than is the case with low density batting. This was incorporated into a mock-up consisting of the heaviest fabric, duck #4, and a thin thermoplastic film to serve the role of added heat sink. The Poly-America film listed in Table 15 served this role. Generally, cigarettes with a TSG test result of 16/20 ignitions and above are required to ignite this substrate though there was at least one anomaly (cigarette 102, with a TSG rating of 12/20 gave six ignitions in six replicates). The Warp Brothers PE film used in the main round robin proved even more ignition resistant.

5. Enclosure Design; Air Flow Considerations

The reason for enclosing the mock-up during a test is to isolate it from random, uncontrolled air currents which could lead to non-reproducible ignition behavior. A very simple open-top enclosure was utilized in the previous study [3]. This was reasonably effective, but it did not completely prevent eddies induced by the laboratory ventilation system from causing occasional visible disturbances of the smoke plume issuing from a cigarette on top of a mock-up. The flow disturbances were measured at up to 8 cm/s. The data from those mock-up tests correlated well with those from full-scale tests in which the air flow disturbances were similarly random (in time and orientation) but of somewhat greater magnitude (12-13 cm/s) [3].

The mock-up enclosure used in the present study is a modification of that designed by the cigarette industry for their own round robin testing. Figure B-1 in Appendix B shows a schematic of the enclosure and the associated smoke exhaust hood. The flow in the neighborhood of the cigarette is sufficiently low that the smoke plume rises totally undisturbed (visually) up into the chimney. Since the cigarette plume must act as a weak pump carrying some air out of the box, some replacement air must flow down the outer portions of the chimney, but its velocity is too low to measure. The oxygen level at the height of a burning cigarette drops no more than 0.1 to 0.2 % (below normal ambient levels) when a cigarette burns its full length in this box.

The cigarette industry has expressed concern about the role of ambient air flow and its potential ability to modify the ignition propensity of cigarettes. Changes of greatest concern would manifest themselves as alterations in the rank ordering of the cigarettes' ignition propensities at different air velocities. Of lesser concern is the potential for all ignition propensities to increase uniformly. Assessment of any changes in ignition propensities must consider the reproducibilities of both the study that generates such information and of the cigarette ignition test methods themselves. The former has not been addressed; the latter is discussed below in light of the interlaboratory study results. For the present, it is important to note that shifts in relative ignition propensity must be substantial (*i.e.*, 35% or more) to be judged significant. Cigarette industry staff have made several presentations of their studies of the air flow effects on ignition propensity. The most thorough and meaningful of these, in light of the above caveat, is discussed here.

In reference [20], Adiga *et al.* report on the effects of steady, low velocity flows impinging on cigarettes in the same direction as that in which the coal is moving. (This head-on flow impingement is the worst case with regard to impingement angle [21]. The steady, uni-directional nature of the flow can also be expected to yield a greater impact on the cigarette coal than does a randomly fluctuating flow that includes some flow reversals.) The peak flow velocity used there (5 cm/s on their "breeze tunnel" centerline) gave a flow velocity on the cigarette centerline of approximately 1 cm/sec (4 mm from the wall surface). This is about the same as the average buoyancy-induced velocity level reported by R. Flack (in a study for the cigarette industry) in the crevice region (4 mm from surface) of a chair previously heated by a *ca.* 37 °C heater simulating a person [22]. These real chair results also showed substantial flow fluctuations, including some flow reversals. While these are very low velocities, they are comparable in magnitude to those measured very near the top of a cigarette coal during natural smolder when mounted horizontally in free space [23]. Presumably the presence of a horizontal surface below the cigarette coal lowers the local plume velocity even more and renders it susceptible to alteration by small ambient velocities.

The impact of a flow disturbance on the cigarette coal is most likely to be one of increasing the coal temperature somewhat since oxygen transport to the coal will be enhanced. Heat losses will also be somewhat enhanced, but this effect should be smaller since the radiant component is not directly affected. The magnitude of any change in the coal temperature is not readily estimated, however, even from an ignition model because the mass transfer processes in the critical region of contact between coal and fabric are very complex. The impact on the fabric ignition process itself (*i.e.*, the runaway acceleration of fabric char oxidation reactions) may not be negligible. This runaway is somewhat retarded by oxygen depletion below the coal [3], and air flow could affect this.

The overall consequences of very low ambient velocities such as were noted above are ambiguous at present. The impact of disturbing the air in the NIST enclosure was examined experimentally. A small fan of the type used to vent electronics cabinets was mounted in one corner of the enclosure at mid-height. The fan speed was controlled with a variable transformer and its RPM was set with precise repeatability using a stroboscope. The fan blew upward so as to effect throughout the enclosure volume a large, recirculating eddy-like flow which passed over the cigarette atop a mock-up with the flow generally impinging head-on. The flow velocity fluctuated from 4 to 13 cm/s (uni-directional), blowing the smoke plume over at an angle that varied from 30° to 90° off vertical.[4] Even though some smoke accumulated in the enclosure in these circumstances, the oxygen level at the height of the cigarette did not drop more than 0.2% below ambient except when mock-up ignition was well along. Table 17 shows there was no significant effect of this flow.

When the fan RPM was doubled, yielding flow velocities that fluctuated in the range from 10 to 25 cm/s, cigarettes 108 and 508 did respond with a significant increase in the number of mock-up ignitions. Cigarettes 106, 130, 506, 508 and 529 did not; the other cigarettes all yielded essentially 100% ignitions under all conditions.

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[4] These flow velocities must be regarded as approximate since they were at the low end of the capability of the anemometer used. The plume behavior was very clearly altered over its full height, however.

Table 17. Effect of Air Flow Disturbance on Cigarette Ignition Propensity
Duck #6, Percent Ignitions

Cigarette # (TSG Ign. Frac.)	Replicates	No Flow	Flow	Double Flow
106 (1/20)	4	0	0	0
130 (4/20)	4	0	0	0
108 (7/20)	4	25	25	75
102 (12/20)	4	100	100	100
121 (14/20)	4	75	100	100
109 (15/20)	4	100	100	100
128 (20/20)	4	100	100	100
506	16	0	0	0
508	16	0	0	56
529	16	12	25	19
530	16	0	0	0

Adiga *et al.* [20] used the Series 500 cigarettes and cotton ducks stated to be comparable to those used here. Their polyurethane foam was 25% lower in density than that used by NIST; but, as noted above, we have found little effect of such a density difference. They also found a rather minimal response from cigarettes placed atop duck #6, although cigarettes 530, 505 and 529 did show some ignitions (10-30 %) at a steady, head-on airflow velocity of approximately 1 cm/s (cigarette centerline); with no flow these three cigarettes gave no ignitions. The lighter cotton ducks (#8, #10, #12) showed an increasing response to the same air flow, with the response being greatest for the lightest duck. In all cases, however, while the absolute number of ignitions went up, the relative ranking of the tested cigarettes remained similar to that seen with their TSG analogs. This type of result, an upward shift in number of ignitions with small changes in relative cigarette ignition propensity rankings, implies that testing with or without an ambient flow would produce little practical difference. In assessing results of this type one has to bear in mind the degree of reproducibility of the test and the limits this imposes on the ability to make distinctions in cigarette ranking. The reproducibility of the mock-up test method developed here is discussed in the context of the interlaboratory study below.

Adiga *et al.* [20] also examined the influence of air flow on the ignition behavior of the Series 500 cigarettes with two other fabrics, a blue denim and California Standard velvet. These are nominally the same as two of the fabrics used in the TSG study, except that they were doped with potassium acetate in this study to enhance their ignitability.[5] The doped California velvet proved to be too readily ignited by most of the Series 500 cigarettes to provide much information on air flow effects. The behavior on the blue denim was more complex. There was an increase in ignitions as the potassium level was increased, even in the no-flow case. At any given level of potassium, the presence of a steady air flow (*ca.* 1 cm/s at the cigarette centerline) enhanced the number of ignitions still further. The most distinctive anomaly in all of this is the observation that three of the cigarettes [505 (BELC-21), 506 (BELN-21), and 508 (BEHN-21)] showed a relatively stronger response to the air flow, and this tended to alter their ranking substantially relative to the other cigarettes tested. These are cigarettes whose TSG analogs exhibited low ignition propensities. Evidently, in the presence of the particular air flow conditions of this experiment, these cigarettes on this fabric lose their diminished ignition propensity and tend toward the behavior seen with high ignition propensity cigarettes. A physical explanation for this is lacking at this time. The extent to which this result would carry over to the real world is also not known at this time. As noted above, greater flow differences between mock-up and chair tests in the TSG study did not preclude a good correlation between the two types of tests.

In view of the information at hand, it has been judged appropriate to select the no-imposed-flow case as preferable since it clearly is simplest and, on balance, seems quite relevant to the real world. In the real world, the orientation of any flow relative to the cigarette coal is unknown but is probably random; it will depend on where and in what orientation the cigarette happens to fall. Many ignitions may occur down in a crevice-like crack, such as is formed by the seat cushion and the side of the chair; and the air flow there is likely to be very small (smaller than the values measured by R. Flack [22]). Thus, even cigarette designs such as those noted above as having lost their low ignition propensity in some particular sets of circumstances are expected to exhibit low ignition propensity in many real world conditions. Should more information on the response of cigarettes to real world conditions be developed in the future, it may be appropriate to supplement the no-imposed-flow test behavior with other data.

6. Test Variables

In order to optimize the test method specification, a list of parameters was compiled, prior to finalizing the method, with advice from the Technical Advisory Group, to identify possible sources of test variability (Table 18). These were classified by source: substrate type, test environment, test operator and test procedure. Based on the extant data at the time of initial list compilation, each parameter was assigned by NIST a sensitivity level that indicated its possible impact on the test outcome. For a standardized test method, it is desirable to have as many variables as possible determined to be "not sensitive."

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[5] In the TSG study the California velvet was used over cotton batting in a flat mock-up configuration. The blue denim was used in a crevice mock-up configuration with a cover cloth over the cigarette. Neither ignites readily in a simple flat mock-up configuration over polyurethane foam as used by Adiga *et al.*

Based on the various experimental results described above and careful, detailed specification of the test procedure, NIST subsequently moved several of the variables in the "B" and "C" columns to the "A" column. These included:

- additives and impurities of the materials and their physical properties;
- fabric tension, retention method, and configuration; and
- mockup location in the box.

Others were assigned as variables to be assessed during the interlaboratory study:

- the operator variables,
- materials conditioning, and
- relative humidity and temperature in both the conditioning and test rooms.

The series of items under "cigarette ignition procedure" was resolved based upon data from NIST and the cigarette industry. These studies combined to establish a procedure that had minimal impact on ignition propensity:

- ignition by a gas lighter with a fixed flame size,
- a cigarette pre-burn, in the vertical orientation, to a length of 15 mm subsequent to ignition and prior to cigarette placement on the substrate,
- transport in a vertical orientation of the cigarette to the test chamber, so as not to dislodge the ash.

Since no significant changes in ignition propensity had been observed during the course of this study, it was presumed that "fresh" substrate materials did not age substantially over a year.

Table 18 is instructive in that it indicates the large number of variables which must be considered and controlled in order to assure a reproducible test outcome. Most are handled in a prescriptive manner by restrictions on materials and by a very explicit test procedure.

Table 18. Estimated Sensitivity of Mock-Up Test Outcome to Test Variables

A = Not sensitive if carefully controlled; B = Expected to be sensitive; C = uncertain of sensitivity

VARIABLE	A	B	C
SUBSTRATE			
Fabric			
fiber content	X		
additives		X	
impurities		X	
existence and variation in backcoating	X		
existence and variation in fiber coating	X		
yarn twist			X
warp & fill count	X		
air permeability			X
weave type	X		
pile depth	X		
areal density		X	
Foam			
air permeability			X
chemical formulation			X
age		X	
thickness	X		
additives		X	
inorganic content		X	
cell size			X
density		X	
Mockup			
dimensions	X		
fabric tension		X	
randomization of materials	X		
# sides covered by fabric	X		
fabric retention method (*e.g.*, pins)		X	X
configuration (crevice, flat...)		X	
TEST ENVIRONMENT			
enclosure size	X		

VARIABLE	A	B	C
enclosure materials	X		
external air flow	X		
internal air flow	X		
mock-up location in box		X	
relative humidity		X	
temperature			X
OPERATOR			
experience level		X	
glove use in handling mock-ups	X		
mechanical handling of fabric		X	X
handling of cigarette	X		
cigarette placement on mock-up			X
ID of cigarettes	X		
TEST PROCEDURE			
allowed cigarette shelf life	X		
allowed materials shelf life			X
cigarette conditioning			X
mock-up conditioning			X
retrieval of components for test	X		
cigarette ignition procedure			
cigarette smolder line		X	
draw rate on cigarette		X	
ignition time and flame location		X	
movement to test box		X	
orientation of cig. during free burn		X	
ash retention		X	
placement of cig. on mock-up	X		
door closure speed		X	X
definition of ignition	X		
number of replicates	X		

7. General Description of Mock-Up Ignition Test Method

This test method depends on seven components which are considered to be critical:

- a test operator skilled in basic laboratory techniques,
- an environmental room/chamber for preconditioning the cigarettes and mock-up assemblies,
- an environmentally-controlled test room,
- a cigarette lighting apparatus,
- a test chamber,
- a furniture mock-up assembly, and
- the cigarette to be tested.

A photograph of a test chamber containing a mock-up assembly and a cigarette is shown in Figure 1. The test procedure is fully described in Appendix B. The following gives a brief description of the test method.

This test procedure begins with the operator preparing the mock-up assemblies in a conditioned environment. Clean, gloved hands are used at all times during the test procedure when handling mock-ups and cigarettes (to preclude salt contamination). The mock-ups and cigarettes are conditioned for at least 24 hours at 55 ± 5 % relative humidity (RH) and 23 ± 3 °C. After conditioning, the test materials may be moved from the conditioning room/chamber to the test room in sealed plastic bags just prior to testing. The test room is conditioned to the same relative humidity and temperature levels as the conditioning room. (Note the test room conditioning was specified somewhat differently in the preliminary interlaboratory study). The vacuum draw ignition apparatus is calibrated to a flow of 1000 cc/min. The mock-up assembly is placed into the test chamber's center and a cigarette test specimen is selected and weighed. If the cigarette weight falls within the required test range for that lot of specimens, a pencil mark is placed on the seam side, 15 mm from the tip. The vacuum draw apparatus is started and the cigarette is placed into the apparatus holder. A butane gas cigarette lighter with a pre-set, 15 mm high flame is ignited and held to the end of the cigarette for three seconds. The lit cigarette is carefully removed from the ignition apparatus and is moved to the test chamber where it is placed into a cigarette holder located on the center of the mock-up assembly. The chamber door is closed, and the cigarette is allowed to burn down to the 15 mm mark. At this point, the cigarette and holder are removed from the mock-up. The cigarette holder is placed into the test chamber's corner and the cigarette is carefully placed diagonally across the mock-up assembly with the ash located at the center of the mock-up. A stopwatch is started to measure the burning time of the cigarette. If the ash falls off at any point in this process, another cigarette is selected; and the process starts again as above. The cigarette is allowed to burn until one of the following occurs:

- self-extinction of the cigarette,

- the cigarette burns its entire length without igniting the mock-up assembly, or
- ignition of the mock-up assembly.

An ignition is defined as a char zone propagating away from the burning tobacco column by at least 10 mm. The stopwatch is stopped upon observing any of the three final test conditions described above. If the mock-up ignites, it and the cigarette are carefully extinguished. The test results are recorded.

8. Interlaboratory Study of Mock-Up Method

a. Preliminary Considerations

All test methods have some random variation that cannot be controlled easily. Tests performed on materials considered to be identical under presumed identical test conditions do not, in general, produce identical test results. This random behavior is generally attributed to the operator, equipment used, calibration of the equipment and environmental changes. Controllable variability is kept to a minimum by a good written test procedure.

Standardized techniques have been developed for the evaluation of test method variability and precision. Precision, as defined by ASTM, is a concept related to closeness of agreement among test results obtained under prescribed like conditions from a measurement process being evaluated [24]. The approach used to evaluate the precision of a test procedure is an interlaboratory study (ILS), referred to also as a round robin. The guide used for planning the interlaboratory studies reported in this report was ASTM E691, Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method [25].

Results from an interlaboratory study generally provide information on *repeatability*, *i.e.*, a measure of variability within a laboratory, and *reproducibility*, *i.e.*, a measure of variability between laboratories. In addition, interlaboratory studies are often used in the process of test method development since a properly designed experimental plan can help to identify areas of variability which may require additional control. In the work reported here, interlaboratory studies were used for improving the test procedures as well as for evaluating precision and reproducibility.

In planning the interlaboratory test programs reported here many factors were considered. Certain of these were viewed as vitally important. Each of these key requirements was taken from ASTM E691:

- A properly designed ILS will be as simple as possible in order to obtain estimates of within- and between-laboratory variability that are free of unnecessary interferences.
- The design should include at least six laboratories.
- Laboratories participating in an ILS must be <u>qualified</u> to conduct the test procedure.

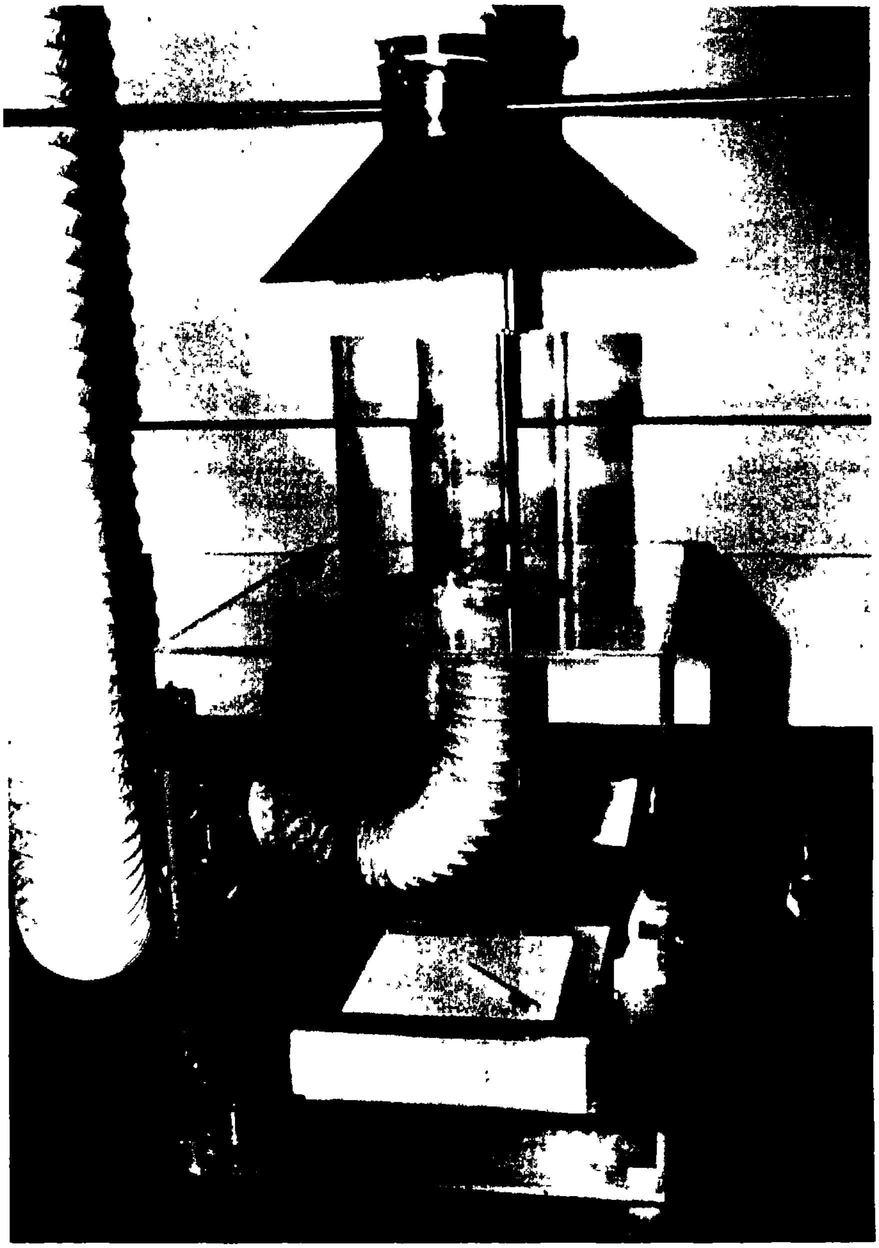

Figure 1. Photograph of a test chamber containing a mock-up assembly and a cigarette.

- The test method should be subjected to a ruggedness test prior to being used in a major ILS. A ruggedness test is generally a small ILS which uses two or more laboratories for evaluating and adjusting requirements in the test method to enhance its function and to identify areas of variability which may need improvement.
- No fewer than three materials, in this case cigarettes, should be used in designing an ILS, and the materials should represent different levels of property measurement.
- The numbers of tests in an ILS should be of sufficient number to obtain a good estimate of repeatability.

b. Selection of Cigarettes for Interlaboratory Study

As described above (Section II.A), the cigarettes for the round robin studies were selected from the Series 500 set; there were insufficient cigarettes from the Series 100 set for this purpose. Series 500, like Series 100, includes 32 different cigarette designs (*i.e.*, variants of tobacco type, packing density, paper citrate content and paper porosity); a smaller subset was chosen for use in the interlaboratory studies.

The size of the subset to be used in the ILS clearly affects the total testing load to be imposed on all participating laboratories, and a compromise between cigarette design diversity and test load was sought. These concerns led to the choice of a three-week test program for the mock-up ignition method and a one-week plan for the cigarette extinction method. The experimental plans were designed to use a balanced selection of five different cigarette types for the study.

Eight of the thirty-two cigarettes in the 500 Series were initially selected as candidates to be used in the ILS. (See Sect. II.A.) These initial cigarette types were chosen to reflect the range of designs found in this group of experimental cigarettes. Packing parameters used in the selection included tobacco type, expanded vs. nonexpanded tobacco, wrapping paper porosity, paper citrate content and cigarette circumference. This initial selection of cigarettes consisted of types identified with the following numbers: 501, 503, 506, 508, 520, 529, 530 and 531.

The second phase of selection, which picked the five cigarettes to be used in the interlaboratory study, was based on the range of ignition performance. Tests were conducted to identify the ignition propensity of the eight cigarettes using the three mock-up assemblies selected for the interlaboratory study. The results are shown in Table 5 (Section II.A). On the basis of these results, the following cigarette types were chosen for the interlaboratory study: 501, 503, 529, 530 and 531. Cigarettes 501 and 503 have relatively high ignition propensities; cigarette 531 has an intermediate ignition propensity and cigarettes 529 and 530, relatively low propensities. The choice of these five cigarettes provides a range of performance which can be used to evaluate the test procedure appropriately. This range of ignition propensity covers that from the population of the experimental cigarettes supplied by the industry for this study. Prior NIST work [3] has shown that the high end of this range was typical of current commercial cigarettes, while the lower end tends to cause few ignitions on any of the tested substrates. Table 19 provides a description of each cigarette type used in the interlaboratory study.

Table 19. Description of Interlaboratory Study Cigarettes

Cigarette Designation	Tobacco Type	Tobacco Expansion	Paper Porosity	Paper Additive	Circumference (mm)
501 BNLC-21	Burley	Non-Expanded	Low	Citrate	21
503 BNHC-21	Burley	Non-Expanded	High	Citrate	21
529 FELC-25	Flue-Cured	Expanded	Low	Citrate	25
530 FELN-25	Flue-Cured	Expanded	Low	None	25
531 FEHC-25	Flue-Cured	Expanded	High	Citrate	25

c. Logging and Randomizing Mock-Up Materials

Logging of Samples. Several systems were implemented to track mock-up materials from product lots. Log books were maintained for the receipt and identification of all materials. Similarly, records were kept on all materials sent to the individual laboratories participating in the interlaboratory study.

Fabric bolts were prepared in runs of approximately 64 linear meters (70 linear yards), and the bolts were numbered sequentially. Each bolt was given an identification number. When a bolt was selected for cutting, the fabric was laid out and marked into 20.3 cm x 20.3 cm (8" x 8") samples. Every sample was identified with a duck number, a bolt number and two additional numbers which indicated the length and width position of the sample in the individual bolt. All numbers identifying a test sample were entered into a permanent log book. The fabrics were handled by gloved personnel and maintained in closed plastic bags prior to mock-up preparation. At approximately 10 meter intervals, a sample was randomly selected from across the width of the goods for ion chromatography analysis.

The polyethylene film samples were tracked, prepared and identified in the same manner as was used for the fabrics. At approximately every 3 linear meters (10 linear ft), a sample was taken for product analysis testing.

The polyurethane foam order consisted of three buns from a sequential production lot. NIST sent an observer to the production plant to verify how the foam was formed, cured, cut and packaged. The lots were marked to indicate the orientation of the foam as it was received off the production run. The packages were disassembled at NIST, and individual foam samples from two of the buns were identified by length and width from the section of the production lot. Every foam piece was logged into a permanent record book. The foam was maintained in closed cardboard boxes.

Randomization of Samples. Fabric samples were randomized according to the following procedure. First, the total number of a cotton duck fabric samples (*e.g.*, duck #4) needed for testing throughout nine laboratories was determined. That number was apportioned, for nearly even distribution, from the number of possible samples obtainable from each bolt of that duck. The appropriate number of samples from a given bolt, was taken randomly and then distributed randomly among the nine laboratories. Laboratory sample logs were prepared by NIST to track samples being sent to the labs (duck no., bolt no., length and width position of sample on the bolt). Test laboratories were instructed to randomize the samples for any given fabric type.

The polyethylene film samples were randomized in the same manner as the fabrics.

Eleven subsections of polyurethane foam were selected at random from the production lot. The individual samples from the foam subsection were identified with two symbols. The foam pieces were then randomly distributed throughout a large, clean room. A number of NIST staff members were asked to randomly select five pieces of foam from the room and place the foam into cardboard boxes. This was then repeated in turn for each foam subsection. At the end of this process, each box contained 55 pieces, 5 pieces from each of the 11 subsections. The test laboratories were instructed to take one box of foam for a given day's testing and to randomize those foam pieces prior to testing.

d. Preliminary Interlaboratory Study

A preliminary interlaboratory study was conducted for evaluation and further refinement of the mock-up ignition method. This study was not designed to validate the new procedure but rather was designed as a screening round to evaluate the effectiveness of the written test protocol and to further study the test method on a multi-laboratory basis. This preliminary round also met the need for a ruggedness test prior to conducting a complete ILS. Three laboratories participated in the preliminary study: Consumer Product Safety Commission, Engineering Laboratory; National Institute of Standards and Technology, Building and Fire Research Laboratory; and Philip Morris USA, Research Laboratory.

In June, 1992, a memo was sent to each participating laboratory providing basic information about the planned study. This memo included a draft of the test method and identified areas where the laboratories might have to make modifications to their test facilities needed for successfully conducting the study. Emphasis was placed on the need for tight control over environmental conditions in the specimen conditioning room/chamber and in the test room. The requirements called for the conditioning room/chamber to be maintained at 50 ± 5% relative humidity (RH) and 23 ± 3 °C and the test room to be maintained at 55 ± 10% RH and 23 ± 3 °C.

Test Operator Training. Each laboratory sent two test operators to NIST for training in July, 1992. One trainee was to be experienced with cigarette ignition testing and the other was to possess only general laboratory skills with no fire test experience. This difference in operator skills would be one of the variables in the ILS. During this training session operators also received detailed instructions on how to report test results. All test operators received a test workbook which contained a copy of the test procedure, a daily weather information form, a test procedure checklist, a fifteen day experimental plan and a daily experimental plan specific to each operator. This book also contained a sample, filled-in worksheet as a guide for the operators and a set of blank individual test worksheets for reporting all tests. In addition, each laboratory received a computer disk containing a program for entering their daily test results. The computer data were used as a backup for the workbooks and also facilitated preparation of a computer-readable data base for use in the data analysis.

Test Chambers and Accessories. Test chamber kits with square brass frames for holding the fabric/film flat on the foam substrate and cigarette holders were prepared at NIST. Several weeks before testing was to begin, the test chamber kits with all accessories and two butane cigarette lighters were shipped to each of the laboratories. The chamber kits provided enough materials to construct five complete test chambers, although only four were needed for the study. Each laboratory assembled their own chambers using directions supplied with the kits.

Test Materials: Cigarettes. Before shipping test cigarettes to the laboratories, NIST took a random sample of cigarettes from each lot and weighed them to determine the acceptable weight range for cigarettes to be tested. The test weight range was plus or minus two standard deviations from the mean value of the sample. A weight range table was prepared and sent to each laboratory with the cigarettes. The participants were instructed to use only cigarettes that fell within the weight ranges specified in the table. All cigarettes that exhibited weights outside of the specified ranges were to be discarded.

Cigarettes were randomly selected from each lot for each laboratory and packaged for shipping. Approximately 200 cigarettes of each test type were shipped to the laboratories by two-day delivery. This quantity provided enough cigarettes to allow for losses resulting from specimens that were out of the acceptable weight range or were damaged and for retests if materials were discarded from aborted tests.

Test Materials: Mock-Ups. The three mock-up assemblies described earlier in the text were used: duck #4 with a layer of polyethylene film placed between the fabric and polyurethane foam, duck #6 placed directly atop the polyurethane foam, and duck #10 placed directly atop the polyurethane foam. The experimental plan required each substrate to be tested with each cigarette type 48 times (24 times by each operator). Approximately 280 sets of fabric and foam for each type of mock-up were randomly selected for each laboratory and shipped to them for testing. This provided approximately forty extra mock-up assemblies for each type used in the study. The excess assemblies allowed the laboratories to replace damaged materials or rerun aborted tests.

Laboratory Visits. During the month of August, 1992, the ILS coordinator visited each of the participating laboratories. These visits included a review of laboratory arrangements for testing, an air flow calibration check for each test chamber, a standard relative humidity calibration for each laboratory, and a review of the test program protocol and test method. The visit also provided opportunities for discussing any last minute questions which the participants had before beginning the test program. The preliminary test program began during the last week of August; and all laboratories had completed the test program by the end of September, 1992.

Nature of the Preliminary Test Round. This preliminary test program was carried out using the mock-up ignition method described above. The interlaboratory test plan was developed with assistance from the NIST Statistical Engineering Division, using ASTM E691-87 [25] as a guide. The factorial design used had the following structure:

•	3	Laboratories
•	2	Operators per laboratory
•	5	Cigarette types
•	3	Number of substrates
•	4	Number of test chambers
•	48	Replicates per cigarette per mock-up
•	3	Weeks of testing
•	720	Total cigarette tests per laboratory

Within the factorial experimental design, the following variables were tracked for possible study:

- Operator skill level - experienced or unexperienced
- Time of day - morning (AM) or afternoon (PM)
- Test chamber number - 1, 2, 3 or 4
- Mock-up assembly type - 1, 2 or 3
- Conditioning room relative humidity and temperature
- Test room relative humidity and temperature
- Cigarette ignition propensity

General Test Plan. All tests were to be performed in the prescribed randomized order as specified in the individual operator workbooks. A single cigarette type was tested by both operators on any given day. Both operators conducted their specified tests simultaneously. Each operator was assigned a pair of test chambers to be used during the morning hours and then switched to their co-worker's test chambers during the afternoon. Mock-up assemblies were tested in the order specified in each operator's workbook. The plan resulted in each cigarette/mock-up assembly being tested twice on each day. Individual test results were to be recorded in the workbooks as each test was completed; and each operator was required to complete a daily summary sheet containing all the information on laboratory operations, conditioning room/chamber control and environmental control in the test room. At the end of each day, operators were requested to transfer their data from the workbook to the computer disk data file.

Analysis of Results. When the test workbooks and computer disks were received at NIST, each was carefully reviewed for accuracy. A small percentage of errors of various types was found in the booklets and computer files. The workbooks showed some missing data and showed some mixed units, generally in temperature measurements. The computer files exhibited typos, transposed numbers and mixed units. These irregularities were corrected on the computer files (by reference to the workbooks) before the data were transferred onto combined laboratory computer files and submitted to the NIST Statistical Engineering Division for analysis.

The combined data file contained 2160 (= 720 × 3) lines of data, corresponding to 720 ignition tests per lab for each of 3 labs. Each line of data consisted of the values of 13 variables. The names used for these variables and a description of the information they represent are summarized in Table 20.

Table 20. Variables in Analysis of Preliminary Interlaboratory Study

Variable Name	Description
TST_RSLT	Test Result, coded as: I=Ignition, N=Non-Ignition, S=Self-Extinguishment
LAB	Laboratory Number (1-3)
CIG_TYPE	Cigarette Type (Coded as 1-5, representing Series 501, 503, 529, 530, 531, respectively)
SUBSTRAT	Fabric/Film/Foam Substrate Identifier 1 = Number 4 Cotton Duck 2 = Number 6 Cotton Duck 3 = Number 10 Cotton Duck
Auxiliary Categorical Variables:	
CHAMBER	Test Chamber Number (1-4)
TST_BLK	Test Block (Week of testing, or equivalent group of five test days = 1, 2 or 3)
OPERATOR	Operator (E=Experienced, I=Inexperienced)
AMPM	Time of Day (A=AM, P=PM)
DATE	Date of test (MMDDYY)
Auxiliary Continuous Variables:	
TSTTEMP	Test Room Temperature
TSTRH	Test Room Relative Humidity
CNDTEMP	Conditioning Room Temperature
CNDRH	Conditioning Room Relative Humidity

Except for DATE, all of the variables in Table 20 were studied in the statistical analyses. The DATE variable was used primarily in the process of checking the data files.

In reporting the test results (TST_RSLT), the laboratories made a distinction between two distinct types of non-ignition outcomes, as follows. For a cigarette which extinguished before the entire tobacco column was burned, the outcome was coded as S, for Self-Extinguishment. Alternatively, when the tobacco column burned all the way to the end without igniting the fabric substrate, it was coded as N, for Non-Ignition.

The test results for the preliminary round are summarized by LAB, CIG_TYPE, and SUBSTRAT in Table 21. The distinction shown there between Self-Extinguishment and Non-Ignition was not used formally in the statistical analysis of the results. Instead, a simpler presentation and analysis were obtained by combining the two types of non-ignition. Thus, a derived variable, named "IGN," was defined as follows:

IGN = Y if TST_RSLT = I (ignition)
= N if TST_RSLT = N or S (non-ignition).

A graphical summary of the test results for the preliminary interlaboratory study, based on the derived variable, IGN, is shown in Figure 2. In this figure, the height of each vertical bar represents the proportion of test runs resulting in ignition (IGN=Y) obtained by the corresponding laboratory for the substrate and cigarette indicated. The 15 bar charts are arranged in a pattern with three rows, corresponding to the three substrates (mock-up configurations) used in testing, and five columns corresponding to the five cigarette types tested. The order in which the cigarettes are shown is based on the total number of ignitions for each cigarette type, with cigarettes having the highest ignition propensity on the left and those having the lowest ignition propensity on the right. (Cigarettes 503 and 501 actually had the same number of ignitions in the preliminary interlaboratory study. Cigarette 503 is shown first in Figure 2 based on the fact that 503 had the most ignitions in the main interlaboratory study described below. Except for the tie between cigarettes 503 and 501 in the preliminary round, the ordering of the cigarettes based on total number of ignitions was the same in the two rounds of interlaboratory tests of the mockup ignition test method.)

It should be observed from the summary shown in Figure 2 and Table 21 that the lab-to-lab variation in the proportion of ignitions is not excessive in comparison with the amount of variation that is commonly found in fire testing. (See below in discussion of main interlaboratory study.) In fact, the largest deviation of any single lab value from the mean proportion of ignitions was about 0.15, which occurred for cigarette 529 on substrate 3 (duck #10). Thus, based on this simple criterion, the mockup ignition test method showed promise of utility.

The participating laboratories were instructed to control the test environment so as to maintain the temperature and humidity variables within defined limits. The data showing the actual range of these variables in the preliminary round are summarized graphically in Figure 3.

Table 21. Summary of Test Results for Preliminary Interlaboratory Study

Cigarette Type	Substrate	Laboratory	Test Results		
			Ignitions	Non-Ignitions	Self-Extinguishments
1	1	1	48	0	0
		2	40	8	0
		3	36	12	0
	2	1	48	0	0
		2	48	0	0
		3	48	0	0
	3	1	48	0	0
		2	48	0	0
		3	48	0	0
2	1	1	47	1	0
		2	35	13	0
		3	42	6	0
	2	1	48	0	0
		2	48	0	0
		3	48	0	0
	3	1	48	0	0
		2	48	0	0
		3	48	0	0
3	1	1	0	0	48
		2	0	0	48
		3	0	0	48
	2	1	3	0	45
		2	0	0	48
		3	3	0	45
	3	1	13	0	35
		2	8	0	40
		3	21	0	27