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Quantifying the Ignition Propensity of Cigarettes†

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Research funded under the Fire Safe Cigarette Act of 1990 (United States Public Law 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.

INTRODUCTION

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.

Alleviation of this problem could proceed along various lines. Decreasing the cigarette ignitability of these furnishings is one approach; the voluntary program promoted by the Upholstered Furniture Action Council addresses the ignitability of upholstered furniture, for example. Alternatively, one might attempt to reduce the propensity of commercial cigarettes to cause such ignitions. This has the advantage of having a shorter lead time in affecting the incidence of these types of fires since cigarettes have a much shorter life cycle than does furniture.

The technical feasibility of cigarettes with reduced ignition propensity was confirmed in a previous study[2,3] (referred to in this paper as the TSG study). That study employed a variety of realistic upholstery materials (in the form of upholstery mock-ups); however, these lacked any demonstrated controllability of properties over extended time periods. Those materials (particularly the fabrics) were thus not suitable as constituents in a possible regulatory test method for assessing cigarette ignition propensity.

This paper describes the results of research that form part of an assessment of the practicability of developing a performance standard to reduce cigarette ignition propensity. The focus here is on the final form of two test methods for cigarette ignition propensity; complete details of the development of these tests, as well as other alternatives which were considered can be found in reference 4. The first of the two methods described here, the *Mock-Up Ignition Test Method*, uses three types of simulated upholstery cushions, each with a different cigarette ignition susceptibility. The *Cigarette Extinction Test Method* replaces the more complex substrate of the Mock-Up Ignition Test Method with standard cellulosic filter paper.

Both of these methods are intended to fulfill two potential roles: (1) as the basis for a possible performance standard, and (2) as 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 did not address specific regulatory criteria.

The performance of a limited set of commercial cigarettes was examined using these tests. The results are reported below.

TEST METHODS DEVELOPED IN THE PRESENT STUDY

Mock-Up Ignition Test Method

Previous work. An upholstery mock-up is in some respects a close 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

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upholstery materials to cigarette ignition. Much of this work is reviewed in reference 5. Essentially all 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[6]. More recently, the TSG study[2] concluded that upholstery mock-ups are also reasonable indicators of the ignition propensity which cigarettes can be expected to exhibit on full-scale chairs.

Ihrig *et al.*[7,8] performed limited studies of the effect on ignition behavior of cigarette design variables along with a broader look at mock-up design variables. They inferred that fabric variables (alkali metal content, weight and density) dominated the ignition process. Polyurethane foam permeability to air flow and cigarette radiative heat output were also seen as significant variables. Overall, mock-up variables were inferred to be of greater import than were cigarette variables.

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.

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.

Fabric considerations. The principal focus in this study of mock-up systems capable of long-term reproducibility has been the nature and 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 ignitability of a cellulosic fabric is its content of alkali metal and alkaline earth cations.[9] Sodium and potassium ions are particularly prevalent in such fabrics.[7,8,9] Potassium ions 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]

The smoldering ignitability of a fabric is also influenced by its physical characteristics; this is particularly true when the ignition source is a cigarette. The influence on the cigarette coal of contact with the mock-up surface 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. There is no practical way to characterize quantitatively the relative popularity of the thousands of upholstery fabrics used in the soft furnishings that are at risk to fire. 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 fibers 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 (1) perfectly even finish surface characteristics and adhesion are difficult to obtain in commercially-produced fabrics and (2) some finishes may promote or prevent smoldering ignition of the fabric
- Weight in the range representative of fabrics that are commonly used in the commercial upholstery fabric marketplace (0.17–$0.85\ \mathrm{kg\,m^{-2}}$, 5–$25\ \mathrm{oz\,yd^{-2}}$). Fabrics below about $0.34\ \mathrm{kg\,m^{-2}}$ ($10\ \mathrm{oz\,yd^{-2}}$) tend to wear rapidly; those above $0.85\ \mathrm{kg\,m^{-2}}$ ($25\ \mathrm{oz\,yd^{-2}}$) 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.*;[7,9] (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;[4] (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; this proved to be problematical.[4] The cotton ducks that were ultimately used have a cation level that assures smolder propagation in their as-received state (see below).

Cross-referencing available fabric types against the needed fabric characteristics noted above led NIST to the selection of cotton ducks. These have a simple physical structure (plain weave) subject to control of weave details and at least limited usage as upholstery fabrics. They present a smooth surface to the cigarette coal,

Table 1. Specified nominal properties of fabrics

Fabric designation	Areal density	Yarn count (per inch)	Yarn plies	Air permeability[a]
Duck no. 4 Style S/01400240	0.83 $kg\,m^{-2}$ (24.5 $oz\,yd^{-2}$)	31 × 24	4 × 4	$5.1-10.2 \times 10^{-3}$ $m^3\,s^{-1}\,m^{-2}$ (1–2 $ft^3\,min^{-1}\,ft^{-2}$)
Duck no. 6 Style S/01600230	0.72 $kg\,m^{-2}$ (21.2 $oz\,yd^{-2}$)	36 × 26	3 × 3	$5.1-10.2 \times 10^{-3}$ $m^3\,s^{-1}\,m^{-2}$ (1–2 $ft^3\,min^{-1}\,ft^{-2}$)
Duck no. 10 Style S/01102020	0.50 $kg\,m^{-2}$ (14.7 $oz\,yd^{-2}$)	40 × 28	2 × 2	$10.2-20.4 \times 10^{-3}$ $m^3\,s^{-1}\,m^{-2}$ (2–4 $ft^3\,min^{-1}\,ft^{-2}$)

[a] Measured by Federal Method 5450 (contained in Federal Test Method Standard 191A, July 1978).

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.

Cotton ducks have a long history of usage in a variety of products and are produced in accord with US Government specifications.[10] This information provides a high degree of assurance that cotton ducks will continue to be readily available and to be produced in a consistent and standardized manner.

Cotton duck characteristics. The physical properties of the 100% cotton fabrics used in this study are summarized in Table 1; a somewhat broader range was examined but offered no additional advantages.[4] All were manufactured by West Point Pepperell Mills of West Point, Georgia (now known as Wellington Sears Company).[a] 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). During manufacture 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.

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 7.)

In anticipation of the fabric ignitability behavior discussed below it is worth pointing out here that the evident ease of ignition of the cotton ducks in Table 1 is the opposite of what one might expect from previous literature results. The review of previous work[5] notes that cigarette ignition resistance decreases with

Table 2. Cation content of fabrics used in this study

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

increasing fabric weight. As will be seen below, the observable behavior of the fabrics in Table 1 is opposite to this trend: the heavy ducks yield fewer sustained smolder results than the lighter ducks. The likely reason for this lies in the important distinction between the actual fabric *ignition* event (which occurs unobserved below the cigarette coal and is suppressed by increasing fabric weight) and *sustained smolder spread* away from the cigarette coal (which is enhanced by fabric weight but is precluded if ignition fails). This argument is developed further in reference 4.

The alkali and alkaline earth metal content of cotton ducks is not normally subjected to control and thus is potentially variable with soil, fertilization and growth conditions of the cotton. Blending of raw cotton from various regions and crop years tends to counteract this variability. The overwhelming concern here is the potassium content, since it appears to dominate the smolder behavior of raw cotton; it dominates the weight content of metal ions as well (Table 2).

The manufacturer of these cotton ducks, West-Point Pepperell, supplied information on potassium content in samples from four of their ducks over a four-month period. With the exception of one variable sample, the greatest change was a 23% increase (4700–5800 ppm) in the potassium content of one duck over this period. Changes of this magnitude were found to have no significant effect on the measured ignition propensity of a set of three different experimental cigarettes.[4] Similarly, six experimental cigarettes of varied ignition propensity gave virtually the same results on two #8 ducks, that from West Point Pepperell (4700–5800 ppm potassium) and a similar duck from another manufacturer (3500–5100 ppm potassium).[4]

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.

Areal density is believed to be the most important physical property affecting ignition susceptibility of the cotton ducks. For the samples used in the present program this showed a coefficient of variation of no more that 3.5%.[4] Air permeability may be of interest as a measure of the tightness of the fabric weave. For the present materials a coefficient of variation of 10.5% was found for one bolt of one duck; more typically the variation was half this or less.[4]

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. The second material is a polyethylene film used between the fabric and foam in one mock-up configuration for reasons explained below.

The polyurethane flexible foam used in these test method development studies had the same formulation as that used in the TSG study.[3] The foam is based on a polyether polyol and TDI. It has an indent flexural rating of approximately 21.8 kg (48 lb) and a nominal density of 32 $\mathrm{kg\,m^{-3}}$ (2.0 $\mathrm{lb\,ft^{-3}}$). The nominal air permeability (ASTM D3574[11]) is $2.0\times10^{-3}\ \mathrm{m^3\,s^{-1}}$ (4.25 $\mathrm{ft^3\,min^{-1}}$). 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 $\mathrm{kg\,m^{-3}}$ (1.5 $\mathrm{lb\,ft^{-3}}$) and a nominal air permeability of $2.4\times10^{-3}\ \mathrm{m^3\,s^{-1}}$ (5.0 $\mathrm{ft^3\,min^{-1}}$).

Flat mockups were made with duck #8 and the two foams. Four experimental cigarettes having differing ignition propensities gave results which did not differ beyond the reproducibility of the test method (see below) on the two types of mock-up. Since the foam density variation in this experiment is substantially larger than would occur within any well-specified foam batch ($\pm$ 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.

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 at different stages of the method development and this was found to make a significant difference for two of the cigarettes used in round robin testing. The preferred film (Warp Bros, Inc.; Polyfilm) is 0.13 mm thick and has an areal density of 0.15 $\mathrm{g\,cm^{-2}}$.

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 which can cause variations in the effective local thermal capacitance of the mock-up if not well controlled. 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 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 can introduce reproducibility problems. Tests at CSIRO in Australia have indicated that the outcome of a crevice test (ignition or non-ignition) can be heavily influenced by how firmly the operator places the cigarette in the crevice.[12] 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. No clear conclusion emerges from previous studies[3, 7] as to whether a flat mock-up or a crevice necessarily discriminates ignition propensity more effectively. 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.

In view of these considerations 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 helps assure that the cigarette is placed in the same mock-up 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.

This flat mock-up configuration, consisting simply of a square of cotton duck held in good contact atop a square of polyurethane foam (5.1 cm thick), was subjected to a series of screening tests to determine the degree of ignition propensity differentiation provided by the various fabrics. The cigarettes used were those from the previous TSG study[3] which had been characterized there as to ignition propensity on a limited variety of

Table 3. Percentage ignitions on various substrates for selected cigarettes: flat configuration; four to six 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

upholstery materials; the scale is the number of ignitions out of a possible maximum of twenty. Table 3 shows the behavior of four cotton ducks.

Table 3 indicates that these fabric/foam mock-ups do provide varying degrees of differentiation of the cigarettes. Ducks #6 and #8 are too similar for both to be included in a test method. Duck #10 is more readily ignited. Duck #12 provided only minimal differentiation among the weakest igniting cigarettes and has not been included in the test method. Duck #4, when assessed with a different set of TSG cigarettes, showed behavior not dissimilar to duck #6.

Since it was desirable to have at least one mock-up which would be resistant to all but the most ignition-prone cigarettes, the mock-up based on duck #4 was modified by the addition of a polyethylene film between fabric and foam to achieve additional heat sinking and thus additional ignition resistance. The film mentioned above was chosen for this; its effectiveness is evident in the round-robin results discussed below. The test method thus is based on ducks 4, 6 and 10; only duck #4 uses the added polyethylene film.

Mock-up enclosure. The mock-up is enclosed during a test to isolate it from random, uncontrolled air currents which could lead to non-reproducible ignition behavior. The enclosure used in the present study is a modification of that designed by the cigarette industry for their own round-robin testing. Figure 1 shows a photograph 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 0.1–0.2% (below normal ambient levels) when a cigarette burns its full length in this box.

There is conflicting and incomplete evidence on a possible role of ambient air flow in influencing cigarette ignition of soft furnishings. A study performed for the cigarette industry by R. Flack of University of Virginia concluded by inference that body heat absorbed into an upholstered chair can induce buoyant air velocities of the order of 1 cm s^{-1} across the cushion surfaces, even near (*ca* half cigarette diameter) the juncture of arm and seat surfaces.[13] The flow is not necessarily monotonic in

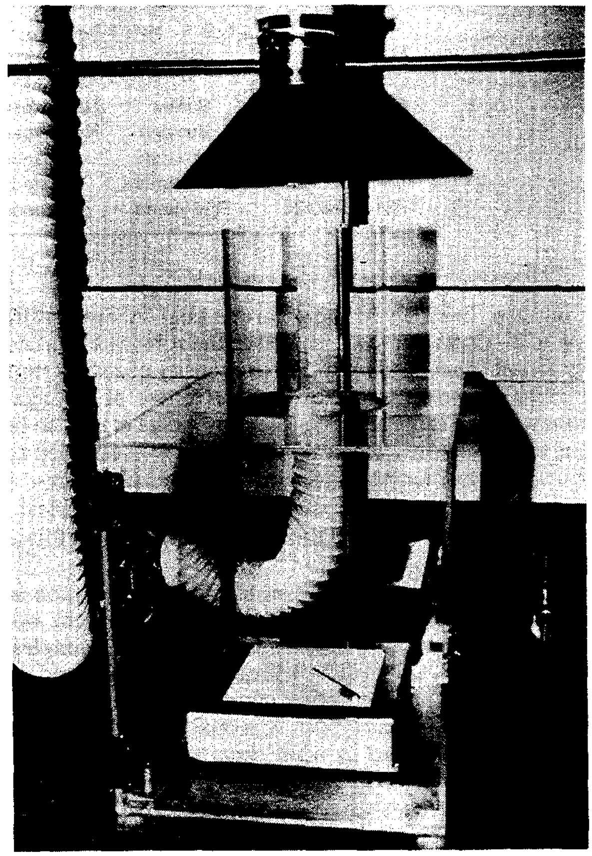

Figure 1. Photograph of a test chamber containing the test assembly for the Mock-Up Ignition Test Method.

direction. Adiga *et al.*[14] tested a variety of experimental cigarettes placed atop flat mock-ups in a laminar flow tunnel with velocities of this magnitude impinging steadily head-on to the cigarette coal. (Head-on impingement has been found to be a worst case for altering the cigarette smolder velocity[15].) Of the various cigarette and fabric combinations tested, three cigarettes on one fabric showed strong sensitivity to this magnitude of flow velocity. The relative sensitivity of these cigarettes compared to others meant that there was a significant shift in apparent ignition propensity ranking of the cigarettes as a consequence of going from no flow to this very small but finite flow. The physical basis for such pronounced flow sensitivity is not known. The same set of cigarettes tested on cotton ducks in this flow tunnel showed enhanced ignition propensity but no shift in relative propensity ranking. This latter type of result is of little concern in a test method but the former result is potentially more worrying.

In contrast to these results, the TSG study[3] found no strong indication of flow effects; differences in flow disturbances between mock-ups $\leqslant 8\ \mathrm{cm\,s^{-1}}$, randomly oriented with respect to the coal) and full-scale chair tests (12–13 cm s^{-1}, also random) did not preclude a correlation between the results on the two scales. In the present study flow disturbances were introduced into the enclosure used by means of a small fan mounted inside, in one corner; this caused a mildly turbulent recirculating flow

Table 4. 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 FELC-25	Flue-cured	Expanded	Low	None	25
531 FEHC-25	Flue-cured	Expanded	High	Citrate	25

to impinge head-on to the cigarette coal. A fluctuating flow of 4–13 cm s^{-1} (*ca* 1 cm above the substrate) had no significant effect on the ignition propensity of a set of nine different cigarettes tested on duck #6; two of the cigarettes were the same as those found by Adiga *et al.*[14] to be flow sensitive. Only when the fan speed was doubled to give flow velocities fluctuating in the range 10–25 cm s^{-1} did one cigarette design show a marginally significant response. (This was one of the two cigarettes Adiga found to be sensitive.)

In view of the (admittedly incomplete) 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 edge 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[13]). 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.

General description of Mock-Up Ignition Test Method. This test method is described in full detail in reference 4; it is summarized briefly here. Figure 1 shows the mock-up assembly inside the air flow enclosure. Both cigarette and mock-up materials are preconditioned to control temperature and moisture level; the test room environment is controlled as well.

A conditioned, weight-selected cigarette is ignited in a prescribed manner using a constant draw device then placed in a vertical holder inside the air flow enclosure. When the paper burn line reaches 15 mm, the cigarette is placed carefully on the center of the mock-up, directly below the chimney. The cigarette is allowed to burn until one of the following occurs:

- The cigarette self-extinguishes
- The cigarette burns its entire length without igniting the mock-up assembly or
- The mock-up assembly shows unambiguous evidence of ignition.

An ignition is defined as a char zone propagating away from the burning tobacco column by at least 10 mm.

Interlaboratory study of the mock-up method. The set of three mock-ups selected as the basis of this test method (ducks # 4, 6 and 10 over a single type of polyurethane foam with duck #4 having a polyethylene film between fabric and foam) was subjected to an interlaboratory round robin to assess both repeatability and reproducibility of the method. (Repeatability is a measure of within lab variability; reproducibility is a measure of lab-to-lab variability.) This was done in two stages with three laboratories participating in a preliminary round to assure that all procedures were viable. Nine laboratories participated in the full interlaboratory study; only those results are summarized here.

Five experimental cigarettes, selected from a larger group supplied by the tobacco industry, were used. Their nominal design parameters, which vary broadly, are shown in Table 4. 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 thus provides a range of performance which can be used to evaluate the test procedure appropriately. Prior NIST work[3] has shown that the high end of this range is typical of current commercial cigarettes, while the lower end tends to cause few ignitions on any of the tested substrates.

The extensive procedural details needed to assure unbiased results are described in reference 4. Each lab performed 720 tests; this was a consequence of 48 replicates of each of 15 different test conditions (three mock-ups used to assess the five different cigarette designs).

Figure 2 shows a summary of the results of the main interlaboratory study. Here, for each cigarette (by columns) and substrate (by rows) the proportion of ignitions is represented by a vertical bar for each laboratory. The cigarette types are shown from left to right in order of decreasing ignition propensity, with cigarette 503 having the most ignitions (in the left-most column of plots) and cigarette 530 having the fewest ignitions (in the right-most column). The three mock-up configurations are shown as rows in the figure, with the least ignitable substrate (duck #4) as the top row and the most ignitable (duck #10) as the bottom row of the figure. For several cigarette and substrate combinations, all laboratories showed either 100% ignitions (charts near the lower-left corner of the figure) or 0% ignitions (those near the upper-right corner). Cases with intermediate ignition percentages fall near the diagonal (upper-left to lower-right) in the figure.

Complete records were kept during the testing of an array of secondary variables which might conceivably influence test results. These included temperature and humidity of both conditioning and test rooms, time of

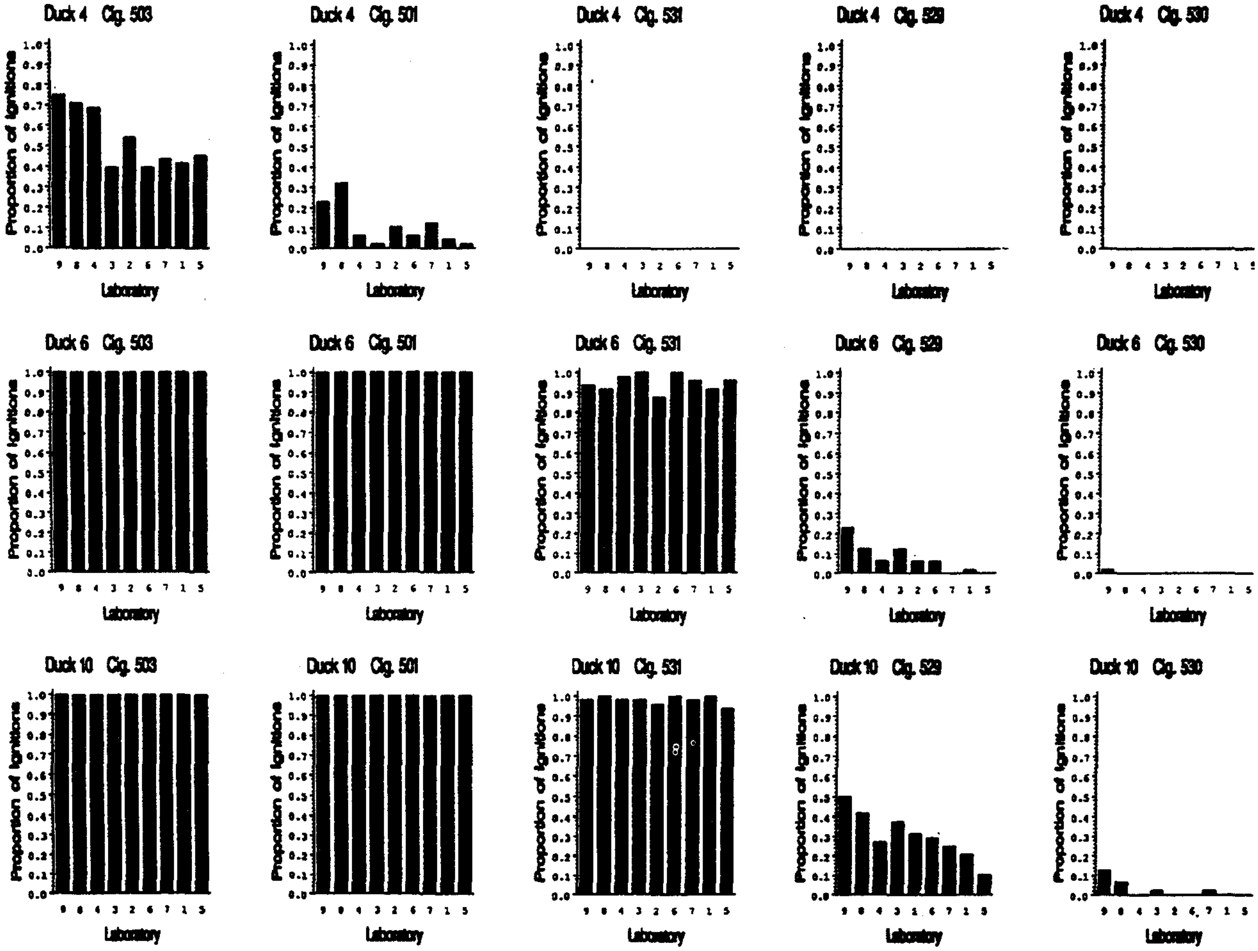

Figure 2. Comparison of ignition rates for the main interlaboratory study of the Mock-Up Ignition Test Method.

day, date, test operator and air flow enclosure (each lab was supplied with five of these because of the large number of test replicates). Overall, the statistical analyses showed some indications of small, but possibly real, dependencies between these secondary variables and the ignition results.[4] However, they did not reveal any major problems in the data. These indications are consistent with the general observation there will always be some means by which the test results could be improved by further refinements to the test method protocols.

The results do show distinct, statistically significant dependencies on the three primary interlaboratory study variables: lab, cigarette and mock-up type. The lab-to-lab variations are the basis for the assessment of repeatability and reproducibility of this test method.

ASTM standard ED-691, Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method,[16] discusses the statistical calculation of repeatability and reproducibility of test methods which yield continuous data. Here the basic data are binary in nature since the outcome of each test is an ignition or non-ignition. The analysis methods of E-691 were adapted to the present study to yield the results in Table 5; the details of this can be found in reference 4.

In Table 5 a statistical model (derived from the interlaboratory results) relating repeatability and reproducibility has been used to infer the 95% confidence limits on these measures of within-lab and between-lab variability as a function of the number of test replicates and the proportion of ignitions. These results apply to any given mock-up and cigarette combination. For example, from Table 5 the reproducibility limit calculated as 0.39 for $m = 48$ runs means that, if two values for the proportion of ignitions are obtained by performing $m = 48$ runs on the same cigarette/mock-up combination in each of two laboratories, then one might expect (95% probability) that the difference between the two proportions will be less than 0.39 if the average cigarette ignition rate is near $p = 0.5$. The table also indicates that the expected difference between two laboratories decreases if the proportion of ignitions is closer to zero or one.

Table 5 allows one to compare the repeatability and reproducibility limits corresponding to several values of m, the assumed number of replications per 'single measurement result'. It is clear from the table, and from the formulas, that repeatability is more strongly affected by increasing the number of replications than is reproducibility. This fact is highlighted in Table 5 by inclusion

Table 5. Mock-Up Ignition Method: calculated repeatability (r) and reproducibility (R) limits for various assumed numbers of replications (m) and ignition propensities (p)

	m =16		m =32		m =48		m =96		m =9600	
p	r	R	r	R	r	R	r	R	r	R
0.05 or 0.95	0.15	0.21	0.11	0.18	0.09	0.17	0.06	0.16	0.006	0.15
0.10 or 0.90	0.21	0.29	0.15	0.25	0.12	0.23	0.09	0.22	0.009	0.20
0.20 or 0.80	0.28	0.38	0.20	0.33	0.16	0.31	0.11	0.29	0.011	0.27
0.30 or 0.70	0.32	0.44	0.23	0.38	0.19	0.36	0.13	0.33	0.013	0.31
0.40 or 0.60	0.34	0.47	0.24	0.41	0.20	0.38	0.14	0.36	0.014	0.33
0.50	0.35	0.48	0.25	0.41	0.20	0.39	0.14	0.36	0.014	0.34

of the case where $m = 9600$ runs is assumed. In general, the repeatability decreases as the square root of m whereas the reproducibility approaches a non-zero limit for large m, which reflects the between-lab component of variability. This behavior shows the limitation to how much the reproducibility precision can be improved by increasing the number of replications within each laboratory.

Results from the interlaboratory study show that the mock-up ignition test method can effectively differentiate the ignition propensities of various cigarettes, albeit at a limited degree of resolution.

The amount by which the reproducibility exceeds the repeatability of this (or any) test method measures the degree to which unknown or uncontrolled influence factors affect the test results in the long term. Data from the nine laboratories in the interlaboratory study show that the ratio of repeatability to reproducibility limits is 1.9 for the mock-up ignition method. This ratio is comparable to that for other fire test methods currently being used to regulate materials which may be involved in unwanted fires. For example, ASTM E 648 (Standard Method for Critical Radiant Flux of Floor Covering Systems) has a ratio of 1.1 to 1.6;[17] ASTM E 662 (Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials) has a ratio ranging from 1.2 to 4.0;[18] and ASTM E1354 (Standard Test Method for Heat and Visible Smoke Release for Materials and Products Using an Oxygen Consumption Calorimeter) has reproducibility to repeatability ratio of 1.8 for ignition delay time.[19]

Cigarette Extinction Test Method

An ignition propensity test method need not directly simulate the upholstery material ignition process. Many flammability tests are imperfect representations of the hazard under consideration. This is because full simulation of the fire of concern is often not possible at bench scale, is too costly, or is otherwise impractical. Thus, a cigarette ignition propensity test method could measure *e.g.* cigarette heat release rate were it shown to correlate with real-world ignition performance. Such a method can be useful in practice, at least over the range of cigarette designs for which it has been calibrated; and it may also be more convenient to apply.

The substrate requirements for a cigarette ignition propensity test method may be more readily met on a long-term basis if upholstery materials are avoided. This prompted the pursuit of alternative methods in this study.

Prior alternative methods. In 1981, Krasny *et al.*[20] reported a series of experiments that ultimately led to the development of a test method that employed alpha cellulose paper as a surrogate substrate. As possible indicators of cigarette ignition potential, they compared four measures of cigarette behavior to mock-up test results obtained for the same cigarettes on a variety of upholstered furniture substrates. These measures included static burning rate of the cigarettes, surface temperature of the cigarette burn cone, burning behavior of the cigarettes in contact with heat sinks, and burning behavior of the cigarettes on alpha cellulose paper. They concluded that weight loss rate from the cigarette/paper system was a good measure of cigarette ignition propensity, while there were shortcomings with the other three measures. Thirty commercially available cigarettes were evaluated by this test method. Reasonable agreement was found between cigarette propensity to ignite upholstered furniture substrates and weight loss rate of the cigarette/paper system. Subsequent work that was part of the TSG study[3] with experimental, low ignition propensity cigarettes showed that the alpha cellulose paper would not smolder, and the cigarettes would all self-extinguish. This resulted in no recorded weight loss and, therefore, no discrimination between cigarettes.

Norman[21] investigated several methods for assessing cigarette ignition propensity. Using four different experimental cigarettes, he measured the heat transfer rate to a receiver below the cigarette coal, the total heat release of a cigarette smoldering in air, the weight loss rate of various cigarette/substrate systems, and the imprint of a cigarette smoldering on a block of polyurethane foam. While Norman could not correlate free-burn heat transfer data for cigarettes burning in air to ignition propensity and the weight loss rate was dependent on specific characteristics of the substrate, the foam imprint method appeared to hold some promise. Gann *et al.*[3] further pursued this latter method. Rather than measure the volume of the imprint, they measured the weight loss of the foam block after removal of the charred remains of the cigarette. They also recorded weight loss versus time of the cigarette/foam system during the cigarette smoldering process. They found only a weak correlation between weight loss and cigarette ignition propensity as measured by the number of ignitions on a selected group of fabric/foam substrates.

Gann *et al.*[3] also investigated the possibility of using a heated glass plate substrate to characterize cigarette ignition propensity. By adjusting the temperature of the glass plate, they found that cigarettes could be made to smolder their entire length. Commercially available cigarettes smoldered their entire length at ambient conditions. Low and moderate ignition propensity cigarettes would smolder their entire length only when the temperature of the glass plate was raised to between 86°C and 97°C. However, as with the case of the alpha cellulose paper, they noted no difference between the low and moderate cigarettes.

Approaches examined in this study. Variants of the inert glass plate type of substrate were examined in this study. Such materials were pursued because glass is a substance which is readily available, well-characterized, homogeneous and easily re-usable. The variants included glass beads, glass rods and glass fiber filter paper[4]. However, none of the behavior exhibited on these substrates by experimental cigarettes of widely varying ignition propensity correlated well with that ignition propensity.

Reactive substrates undergo significant chemical change when heated by a cigarette coal; in this sense they can present an environment more like that a cigarette sees atop an upholstery cushion. In the present study the need was to identify reactive substrates that have advantages over the foam/fabric assemblies. Thus, these materials have to be readily available, well characterized, highly uniform and reproducible, both within a sample and batch to batch, and smooth-surfaced. With these criteria, cellulosic filter paper again emerged as the choice. Tests showed that its areal density, which is believed to be one of its most important properties here, varies by only 1% or less;[3,4] it readily meets all the other criteria as well.

It should be noted that the metal ion concentration is very small in this paper with the result that it will not smolder. When the cigarette extinguishes, the filter paper substrate will cease to react. The filter paper thus appears to be a largely passive heat sink to the cigarette coal and the strength of this sink can be increased by increasing the number of sheets of paper upon which the cigarette sits. Initially it was assumed that the smoldering rate of a cigarette in contact with this varied heat-sink substrate could be used as an indicator of coal strength and thus ignition propensity. This proved too insensitive to be useful, however.[4] Instead, it was noted that, as the number of filter paper layers was increased, specific cigarettes would not burn their entire length. In subsequent work it was found that the ignition propensity of various experimental cigarettes correlated well with the number of sheets of filter paper required to just cause extinction of the smoldering cigarette coal.[b] This became the basis for the cigarette extinction test method.

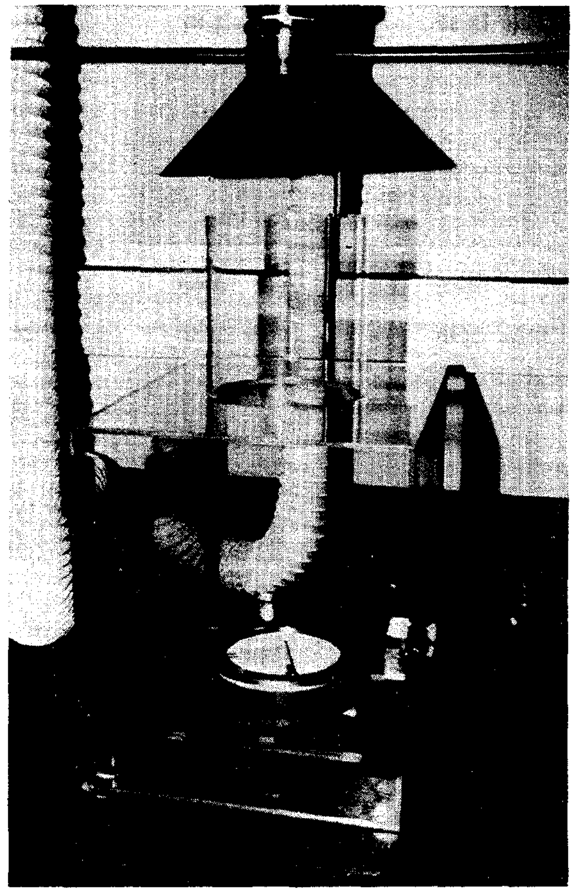

Figure 3. Photograph of a test chamber containing the test assembly for the Cigarette Extinction Test Method.

There is some analogy between this method and the mock-up method. Both vary the heat-sinking properties of the substrate in contact with the cigarette, one with varied weights of cotton duck and one with varied numbers of filter paper layers. The mock-up method is more complex, however, in that the substrate may or may not ignite and forced extinction of the cigarette coal is not the whole story. Full-length burning of the cigarette with no substrate ignition was a not-uncommon response in that system.

A suitable holder ring assembly was designed which keeps a variable number of filter paper sheets flat and has provision to prevent the cigarette from moving during its burn atop this substrate. Figure 3 is a photograph of this assembly inside the same air flow enclosure as is used for the mock-up test method.

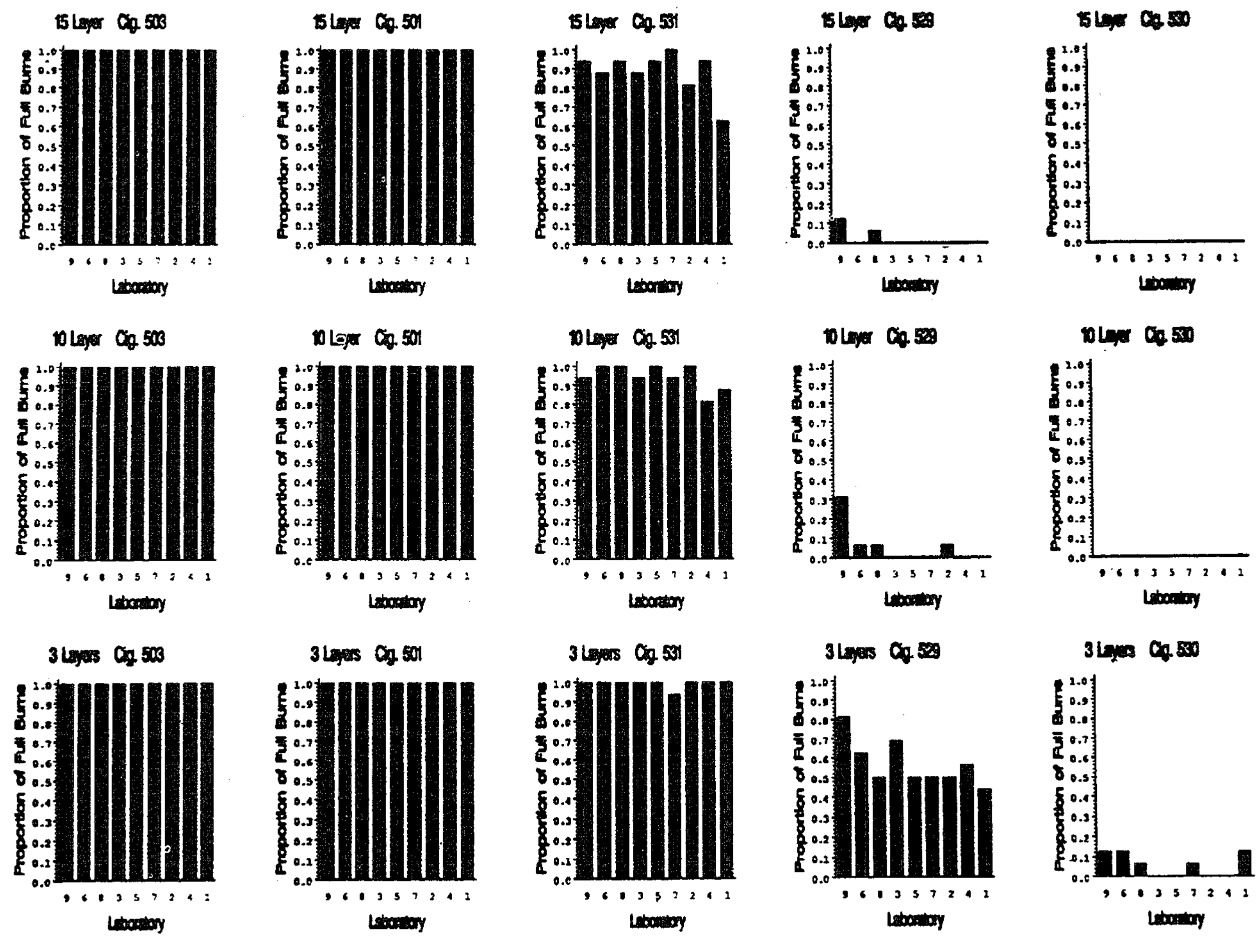

Figure 4. Comparison of ignition rates for the main interlaboratory study of the Cigarette Extinction Test Method.

The test method concept originally involved determination of the actual number of filter paper layers necessary to just allow the cigarette to burn its complete length. To reduce the testing burden on the participating laboratories as well as to reduce the amount of filter paper used in each cigarette evaluation, the interlaboratory evaluation was performed with three specific numbers of layers. This also enabled using a statistical design comparable to the one used for the mock-up ignition test method. The substrates comprised three, ten and fifteen layers of Whatman #2 filter paper. In practice, the original concept may have application as well.

General description of the test method. A detailed description of the cigarette extinction test method, which is quite similar in procedure to the mock-up method, is given in reference 4. In brief, the test method measures whether a given cigarette continues smoldering after being placed on substrate assemblies that have different thermal absorptivities. The appropriate number of layers of Whatman #2 filter paper is mounted in the support structure described above and placed in the enclosure. The cigarettes and substrate assemblies are conditioned at a relative humidity of 55 ± 5% and a temperature of 23 ± 3°C. Cigarettes are ignited and pre-burned to a 15 mm mark as described for the Mock-up Ignition Test Method. The principal determination is whether the cigarette burns its full length or not.

Interlaboratory study of the test method. The nine laboratories participating in this phase of the interlaboratory study were the same as in the study of the mock-up method. Also, the general test protocol for this phase of the ignition propensity study was the same. The only major difference was that fewer replicates were performed. This was proposed since the substrate variability, thought to be a potential factor in the precision in the mock-up method, was minimal here. Thus the same five cigarette designs were employed, being tested on three filter paper substrates (three, ten and fifteen sheets thick) but each condition was replicated only sixteen times. The test results are summarized in Fig. 4 in a manner exactly analogous to those for the mock-up method. Here proportion of full-length burns for a given cigarette atop a given substrate replaces the proportion of ignitions.

Statistical analysis for the effects of secondary variables (environmental conditions, time of day, air flow enclosure, etc.) revealed only rare indications of statistically significant correlations (e.g. one lab for one cigarette). Nothing else unusual was found regarding the data and they were used in the repeatability and reproducibility assessment without modification.

Table 6. Cigarette Extinction Method: calculated repeatability (*r*) and reproducibility (*R*) limits for various assumed numbers of replications (*m*) and full-length burn proportions (*p*)

	$m=16$		$m=32$		$m=48$		$m=96$		$m=9600$	
p	r	R	r	R	r	R	r	R	r	R
0.05 or 0.95	0.15	0.16	0.11	0.12	0.09	0.11	0.06	0.09	0.006	0.06
0.10 or 0.90	0.21	0.22	0.15	0.17	0.12	0.15	0.09	0.12	0.009	0.08
0.20 or 0.80	0.28	0.30	0.20	0.23	0.16	0.20	0.11	0.16	0.011	0.11
0.30 or 0.70	0.32	0.34	0.23	0.26	0.19	0.22	0.13	0.18	0.013	0.13
0.40 or 0.60	0.34	0.37	0.24	0.28	0.20	0.24	0.14	0.19	0.014	0.14
0.50	0.35	0.37	0.25	0.28	0.20	0.24	0.14	0.20	0.014	0.14

Statistical tests were carried out to examine whether these interlaboratory study data reveal differences between the labs, cigarette types and substrates. For labs, there is a statistically significant difference only for cigarette 529 on the ten-layer substrate. The fact that only one case showed a difference for the Cigarette Extinction Method is at least partly due to the fact that only sixteen replications were done per laboratory, rather than the 48 in the interlaboratory study of the mock-up method. With fewer data, fewer significant differences are likely to be found, even if the long-run differences are about the same.

Except for the fact that cigarettes 503 and 501 gave identical results (100% full-length burns for all labs and all substrates) the Cochran–Mantel–Haenszel statistical procedure used here showed that the cigarettes differ from each other. Similarly, the observed differences between the substrates are all statistically significant according to the Cochran–Mantel–Haenszel procedure.

Repeatability and reproducibility were assessed by the same procedures as for the mock-up method. The results are summarized in Table 6 for various numbers of replicates as a function of the proportion of full-length burns observed. It will be noted that the values of the reproducibility limits are somewhat smaller for the Cigarette Extinction Method compared to the Mock-up Ignition Method (based on 16 and 48 replicates, respectively). In contrast, the repeatability limits are *exactly* the same.

CONSIDERATIONS REGARDING THE USE OF THE TWO TEST METHODS

Mock-up Ignition Test Method

The mock-up method is a performance-based method that employs a cigarette/ substrate combination bearing a strong (although not perfect) similarity to the real-world fire safety hazard. The relation between the test results and real upholstered chair ignition behavior is traceable through the use in this study of cigarettes calibrated on real chairs in the TSG study.[3,4] The test output is quantitative and provides differentiation among cigarettes of varied ignition propensity. Through choice and control of materials it should provide a stable standard of performance for the foreseeable future.

As is generally the case with fire tests, this method has potential limitations that are a consequence of incomplete knowledge of the real-world scenarios. First, in the apparatus, the ambient atmosphere is perturbed only by the cigarette plume. This case is believed to be a highly relevant analog for real-world accidental ignitions occurring within a chair crevice. However, if further information on real-world ignitions indicates a significant fraction occurring in external air flow conditions *at the ignition location,* it may be appropriate to supplement the results of the current method with those obtained in the presence of a comparable flow. A second limitation is the small number of upholstery substrates used to relate mock-up behavior to real world chairs.[3] It is presumed that this correlation is representative of the aggregate furniture market. The existence of this correlation virtually assures that there will be some real-world benefit in moving toward cigarettes which perform well in this test method. Should sufficient evidence emerge in the future that a large fraction of the furniture at risk does not follow the correlation that was demonstrated in the TSG study, it may be appropriate to replace one or more of the Mock-Up Ignition Test Method substrates.

The interlaboratory study demonstrated the level of lab-to-lab reproducibility one can expect of this method. That reproducibility is an appropriate measure of how finely a test method can differentiate among test subjects for regulatory purposes. It is apparent, then, that the mock-up method cannot make fine distinctions in ignition propensity among cigarette designs. With 48 replicates on a given mock-up, the proportion of ignitions obtained by two separate laboratories can be expected to differ by up to about 0.4. *This places a limit on the degree of resolution possible for regulatory use of the method.*

Finer distinctions than this could be made only within a single laboratory, presumably for product development purposes. In that case, a number of replicates greater than 48 would appreciably improve the differentiation. Reference 4 discusses circumstances under which it may be acceptable to perform fewer than 48 replicates on one or more of the mock-ups without substantial loss of ignition propensity information.

Informal reports of in-progress cigarette industry studies imply that some upholstery fabrics will respond to contact with a lit cigarette in a substantially different manner from that seen with the cotton ducks used in this method.[c] That is, some fabrics may not rank cigarette ignition propensities in the same order as do cotton ducks. Even if this is verified, the implication is that there is uncertainty in the degree to which adoption of this test method will reduce cigarette-related fire losses. It seems implausible that any cigarette designs judged desirable as a result of lesser ignition propensity on cotton ducks would show greater real-world ignition propensity than do current commercial cigarettes.

At present there are insufficient data available to estimate what fraction of real-world furniture might contain fabrics differing substantially (i.e. beyond the reproducibility of the test method) from cotton ducks in their ignition behavior. If further data become available indicating that such fabrics are a significant fraction of the real-world population, it would be an option to supplement the results of cigarette testing using this method with results based on other carefully chosen fabrics.

Cigarette Extinction Test Method

An analog to most of the discussion in the preceding section applies to this method as well. A further pertinent consideration here is the *degree* of differentiation of cigarette ignition propensity. This is reflected in the numbers of layers selected for the test substrates. For instance, were there an interest in better discrimination among cigarettes of high ignition propensity than is shown in Fig. 4, one might be inclined to select 20 or 25 layers to replace the 15 in the first substrate. However, limited data indicate that this increase has no effect on the burning behavior of cigarettes in this test series. Thus, this method is less appropriate than the mock-up method for distinguishing initial progress from current market cigarettes toward those of lower ignition propensity.

The limit on the degree of resolution for this method is similar to that using mock-ups. Table 6 shows that the level of lab-to-lab reproducibility is about 0.4 for 16 replicate tests. Only modest improvement is achievable for a reasonably larger number of tests. It is apparent that the Cigarette Extinction Test also cannot make fine distinctions in ignition propensity among cigarette designs. *Again, this places a limit on the degree of resolution possible for regulatory use of the method.* As above, finer distinctions could be made within a single laboratory by using a number of replicates greater than 16. Reference 4 also discusses conditions under which fewer replicates on some filter paper substrates are acceptable.

Allowable material variability

The lab-to-lab reproducibility seen in each interlaboratory study for the two test methods (Figs 2 and 4) is a result of the variability of the test operators, the laboratory environment, the substrate materials, and the products being tested. Measuring variations in the cigarettes is part of the purpose of testing. Therefore, in order to assure that the test reproducibility is maintained at the observed level, the substrate material variability limits existent in the present study must be applied to all future materials. This may be a more stringent requirement than necessary but, without further study, there is no justification for looser controls on the materials. Specific values of the allowable ranges of all test materials and other test variables are discussed in reference 4.

Effectiveness of the methods

It will be the role of a regulator to determine which (if any) future cigarettes are tested, by whom, how frequently, and to what requirements. The last of these is likely to be based, in part, on the additional degree of life safety desired. The findings of the TSG demonstrated that measurements using mock-ups are reasonable indicators of full-scale performance.[3] The work to date provides modest guidance in relating performance under these new methods to real-world performance.

There are data to 'calibrate' the methods at the high end of the ignition propensity scale. The current commercial cigarettes are associated with the fire losses of today. The commercial cigarette data below and the data on older commercial cigarettes in reference 3 establish typical performance for these cigarettes. In the two new test methods, this 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.

Both the current work and cigarette industry studies[14] demonstrate the performance of cigarettes that never or rarely ignited a variety of substrates. The correlation of mock-up results with chair tests in reference 3 indicates that such results can be expected to be indicative of real-world performance of such 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 three layers of filter paper. This indicator of test results for the low ignition propensity end of the scale is less quantitative than the high end indicator mentioned earlier.

In between these extremes, one would like to be able to predict a reduced number of fires as fewer ignitions are measured in the laboratory. The full-scale tests in reference 3 support this. At least for coarse changes in test performance, real-world savings seem highly likely. When considering smaller increments in test performance, however, one must keep in mind the accuracy limits of the methods as discussed above.

TESTING OF COMMERCIAL CIGARETTES

Having completed the development of standardized testing procedures, NIST has evaluated a sample of current

Table 7. Results of commercial cigarette testing

	Mock-Up Ignition Test Method			Cigarette Extinction Test Method		
Cigarette	Duck #4[a]	Duck #6	Duck #10	15 layers[b]	10 layers	3 layers
1	48/0/0	8/0/0	8/0/0	16/0		
2	48/0/0	8/0/0	8/0/0	16/0		
3	48/0/0	8/0/0	8/0/0	16/0		
4	48/0/0	12/0/0	8/0/0	16/0		
5	48/0/0	12/0/0	8/0/0	16/0		
6	48/0/0	12/0/0	8/0/0	16/0		
7	46/0/2	16/0/0	8/0/0	16/0		
8	48/0/0	16/0/0	8/0/0	16/0		
9	48/0/0	16/0/0	8/0/0	16/0		
10	48/0/0	8/0/0	8/0/0	16/0		
11	48/0/0	8/0/0	8/0/0	16/0		
12	48/0/0	8/0/0	8/0/0	16/0		
13	48/0/0	8/0/0	8/0/0	16/0		
14	48/0/0	8/0/0	8/0/0	16/0		
A	2/5/41	44/0/4	8/0/0	6/10	15/1	6/0
B	35/1/12	44/0/4	8/0/0	15/1	6/0	6/0
C	0/0/48	13/0/35	4/0/4	2/14	8/8	16/0
D	22/1/25	35/0/13	8/0/0	14/2	15/1	6/0
E	0/31/17	46/0/2	8/0/0	15/1	16/0	6/0
F	0/6/42	38/0/10	8/0/0	3/13	8/8	16/0

[a] Results for the Mock-Up Ignition Method are shown in the sequence: ignitions/non-ignitions/self-extinctions.
[b] Results for the Cigarette Extinction Method are shown in the order: full burn/partial burn.

commercial cigarette types. The results of this performance testing:

- Demonstrate the utility of the methods for routine testing of production cigarettes
- Provide baseline data for comparison with commercial cigarettes of the future
- Present examples of the recommended reporting format for the ignition propensity data.

Choice of commercial cigarettes

The cigarettes were chosen with two objectives in mind: (1) to incorporate packings which comprise a significant portion of the consumer market, and (2) to include several packings judged likely to yield a lower ignition propensity compared to the best-sellers. After reviewing available physical characteristic data, fourteen packings in the former category were tested and six in the latter.

Consumer market data were obtained from the 10 February 1992 Maxwell Consumer Report. This includes complete sales data only through 1990, and it is the 1990 data which were used. The Maxwell Report data indicate that the fourteen packings chosen comprised 38% of the market in 1990.

These best-selling brands do not vary widely in physical parameters such as packing density, paper permeability or tobacco rod circumference. Thus a second, smaller group of cigarettes was identified which do show more substantial deviations in their physical parameters. The particular emphasis was on cigarettes having two physical parameters which deviate in a direction which the TSG study[3] would suggest as likely to lower ignition propensity, e.g. lower paper porosity, circumference, tobacco density. The six selected packings comprised less than one per cent of the market in 1990.

Test procedures

The cigarettes were tested nominally using the two procedures described above. However, it was expected that many of these packings would be of very high ignition propensity. Therefore, the full complement of replicates (48 or 16) was performed first for the duck #4 and 15-layer substrates. If 48 ignitions in the Mock-Up Ignition Method were observed, then eight replicates were performed on the remaining substrates. This reduced testing on more ignition prone substrates follows from considerations discussed in reference 4. Also, for certain of the top fourteen packings (4 through 9 in Table 7), additional tests were run on duck #6 before the decision was made to limit the testing to eight replicates. If 16 full-length burns in the Extinction Method were noted, then no further testing was performed.

One of the packings in the group of six selected as less ignition prone (packing C in Table 7) had a tendency to self-extinguish during the vertical free-burn period prior to placement on the substrate. Thus, on duck #6, 13 of the 35 extinguishments occurred during this vertical free-burn. When an additional 24 replicates were run with this duck using a horizontal cigarette orientation during the free-burn interval, 12 caused ignition and 12 self-extinguished on the mock-up. This increase in ignition rate from 27% to 50% is comparable to the repeatability of the method (Table 5) and was not considered sufficient to revise the test procedure. Note, however, that this cigarette was run only with a horizontal free-burn for the tests on duck #10 and the three filter paper substrates.

Analysis of data

Table 7 shows that the top 14 best-selling packings behaved in a virtually identical manner, with packing #7 exhibiting two self-extinctions on duck #4. Both test methods indicate they are strong igniters; neither method reveals any differentiation among these packings. Reference to the interlaboratory study results for the Mock-Up Ignition Method (Fig. 2) indicates that all of these cigarettes are stronger igniters than the two strongest experimental cigarettes (503 and 501) used in that study.

The six packings chosen as likely to be of lesser ignition propensity did in fact show this tendency to varying degrees. Both methods reveal the same qualitative picture: a monotonic increase in the number of ignitions or full-length burns as one moves toward the lighter fabrics or fewer filter layers. Of particular note is that four of these packings (A, C, E, F) showed few or no ignitions in 48 replicates on duck #4. Compared to the Mock-Up Ignition Method, the Extinction Method does not seem to pick up the reduced ignition propensity of one of these (packing E) and also does not distinguish as strongly the performance of cigarettes A and D from the 14 best-selling packings. Packing C shows a persisting tendency toward a lesser ignition propensity, even on duck #10; the Extinction Method does not show this on the ten- or three-layer substrates. These observations are consistent with those in the interlaboratory study, which indicated that the Mock-Up Method is capable of better distinction among cigarettes in the upper/middle part of the ignition propensity range.

Table 8 provides a further check of consistency between the two methods, and thus further affirmation that the measured cigarette performance is consistent across diverse substrates. Here, the ignition strengths of the five cigarettes from the interlaboratory study and five of the second group of commercial cigarettes are tabulated. (The fourteen best-selling commercial packings showed nominally 100% ignitions on all six substrates and thus the data are not informative.) Cigarette C is omitted because the testing was performed using two different pre-burn procedures. The rows are in order of decreasing average of the six values in the row; the columns are arranged similarly. The averages from the interlaboratory study are for 432 replicates (9 labs × 48 each) for the cotton duck substrates and 144 replicates (9 × 16) for the filter paper substrates. The number of replicates for the commercial cigarettes are far fewer and shown in Table 7.

There is a generally consistent decrease in ignition strength from the top-left corner of the matrix to the lower-right corner, especially considering the reproducibility of the data established in the interlaboratory study. Perhaps the largest single departure from the general pattern in the table is for either cigarette 501 or cigarette D tested on the duck #4 substrate. However, these cigarette ignition propensities are quite comparable to each other. The two duck #4 values are within the established interlaboratory reproducibility of each other, and both cigarettes yield similar results on all the other substrates.

As in the TSG studies,[3] it is of interest to determine whether reduced ignition propensity necessarily results in increased yields of undesirable smoke components. The mean values and standard deviations for the two sets of commercial cigarettes tested here are shown in Table 9. The entries in Table 9 were compiled from data contained in reference 22. These data were generated by the Tobacco Institute Testing Laboratory. The results show that reduced ignition propensity has been achieved with no significant increase in these three smoke components.

Table 8. Percentage ignitions or full-length burns on test method substrates

Substrate → / Cigarette ↓	3 layers	Duck #10	10 layers	Duck #6	15 layers	Duck #4
B	100	100	100	92	94	73
503	100	100	100	100	100	53
501	100	100	100	100	100	11
D	100	100	94	73	88	46
E	100	100	100	96	94	0
531	99	98	94	95	88	0
A	100	100	94	92	38	4
F	100	100	100	79	19	0
529	57	30	6	8	2	0
530	6	3	0	0	0	0

Table 9. Averaged smoke component yields from commercial cigarettes (mg per cigarette)

Cigarettes	Tar (mg)	Nicotine (mg)	Carbon monoxide (mg)
1-14	14.4±4.2	1.04±0.27	13.7±2.2
A-F	11.7±4.8	0.98±0.38	12.5±6.2

CONCLUSIONS AND RECOMMENDATIONS

The research funded under the Cigarette Safety Act of 1984 (P.L.98-567) and 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.

The fourteen best-selling commercial cigarette packings and six other commercial packings were examined using the two methods. Both methods showed reduced ignition propensities for five of the six specialty cigarettes relative to the best sellers.

For a product standard at present, there is a preference for using the Mock-Up Ignition Test Method because it is capable of better discrimination among cigarettes of high/moderate ignition propensity. However, 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 ignition behavior in full-scale chairs constructed using fabrics that differ substantially from the materials in the test methods. It is reasonable to assume that this implies an analogous benefit of reduced ignitability is to be found in the real-world population of upholstered furniture. However, the *precise* incremental life and property savings that would accrue from the use of the test methods described here in conjunction with a particular test criterion has not been established.

Both methods have been subjected to interlaboratory study. The resulting reproducibilities were comparable to each other and comparable or superior to most currently-used standard fire tests.

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NOTES

[a] Certain commercial materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply the material identified is necessarily the best available for the purpose.

[b] Note that there is nothing to be gained by going to an indefinitely greater number of sheets. The heat from the cigarette can penetrate only so far in the time available. It is estimated that 25–30 sheets constitute a thermally thick medium and the heat sinking effect can be expected to diminish before this number is reached.

[c] Equally informal analysis of the industry data shows that, in the aggregate, the population of available fabrics behaves similar to the cotton ducks in assessing cigarette ignition propensity.

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