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The roles of standard cigarettes in assuring the ignition resistance of soft furnishings

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Summary

Regulations for cigarette ignition resistance (CIR) of soft furnishings (beds and upholstered furniture) and less fire-prone cigarettes have contributed substantially to the decrease in losses from cigarette-initiated fires over time. Two standard reference cigarettes play key roles in mitigating these losses and in sustaining the effectiveness of the fire safety regulations as exogenous changes occur. SRM 1082 provides a uniform, durable supply of cigarettes for use in ASTM E2187 that assures manufacturers and regulators of compliance with regulations for reduced ignition propensity cigarettes; enables quality control of cigarette fire test performance; enables assurance of uniform interlaboratory test results; obviates effects on fire safety as tobacco crops and smokers change over time; and, when the original ASTM E2187 substrate material was no longer available, enabled adding a new, equivalent substrate. SRM 1196 provides a uniform, durable supply of cigarettes for assurance of consistent interlaboratory evaluation of the ignition resistance of soft furnishings using the mandated test methods; obviates possible unknown changes in soft furnishings' CIR due to the evolving ignition strength of the original test cigarette over time; and provided a test cigarette that was stronger than most cigarettes being smoked after manufacture of the original commercial test cigarette ceased.

KEYWORDS
bed fire, cigarette, fire, fire safety, furniture fires, ignition resistance, SRM 1082, SRM 1196

1 | BACKGROUND

For four decades, soft furnishings (RUF and beds) have been reported as the most common first items ignited and/or the principal factor in fire growth in fatal fires in the U.S..[1] This was largely due to many of these items having a large mass of padding material and upholstery fabrics that (a) were ignitable by common ignition sources and (b) exhibited rapid fire growth and sufficient combustible mass to sustain a high HRR. These characteristics result in little time for occupants to recognize the fire and take actions necessary for survival.

There have been two regulatory approaches to addressing the fire hazard of soft furnishings:

- Limit the size of the fire, that is, the heat release rate of soft furnishings. This reduces the threat to building occupants, especially those away from the fire room. A high HRR can lead to room flashover, either from the initial furnishing item alone or by igniting

Abbreviations: ASTM, ASTM International; BHGS, (California) Bureau of Home Goods and Services; CFR, Code of Federal Regulations; CIR, Cigarette ignition resistance; CPSC, (U.S.) Consumer Product Safety Commission; CTC, Commercial test cigarette; FSC, Fire standard compliant; HRR, Heat release rate; ILE, Interlaboratory Evaluation; ISO, International Standards Organization; NBS, National Bureau of Standards (now NIST); NFPA, National Fire Protection Association; NIST, National Institute of Standards and Technology; PFLB, Percentage of full-length burns; RUF, Residential upholstered furniture; SIS, Standard ignition source; SP, Special Publication (NIST); SRM, Standard Reference Material (NIST); TAG, Technical Advisory Group (Fire Safe Cigarette Act of 1990); TB, Technical Bulletin (California); TN, Technical Note (NIST); TSG, Technical Study Group (Cigarette Safety Act of 1984); UFAC, Upholstered Furniture Action Council; U.K., United Kingdom.

other combustibles in the room. A post-flashover fire can threaten the safety of people throughout the residence.
- Mandate resistance to ignition. This reduces the number of fires and protects people intimate to the ignition site.

There has been no regulation of the HRR from *residential* furniture. California Technical Bulletin 133 (TB 133)[2] provided for full-scale testing of upholstered furniture used in *public occupancies* that were not protected by automatic fire sprinklers. TB 133 was withdrawn effective January 22, 2019 since the California building code requires the installation of fire sprinklers in public buildings.

Effective July 1, 2007, the Consumer Product Safety Commission (CPSC) has required full-scale testing of mattresses and mattress sets under 16 CFR Part 1633.[3] This standard severely limits both the peak HRR and the early heat release to levels that were determined to reduce the threat to life safety.[4] Analysis of United States fire incidence data shows that this standard has already significantly reduced the fatalities from bed fires ignited by flaming ignition sources.[5] Full-scale mattress testing using California Technical Bulletin 121[6] for prison mattresses and Technical Bulletin 129[7] for public buildings (and their analogous standards ASTM E1590 and NFPA 267) limit the HRR of mattresses in public occupancies.

There has been extensive effort devoted to reducing the number of ignitions of soft furnishings fires, the largest number of which are due to lit cigarettes.[8,9] The process by which cigarettes ignite soft furnishings is a combination of heat transfer and materials chemistry. The geometry of the cigarette-furnishing item is shown in Figure 1.

A cigarette is a very weak heat source, generating approximately 8 W.[10,i] When the lit cigarette falls on a bed or chair, it uses some of the heat to keep the cigarette smoldering, radiates some heat to the surroundings, and applies the remainder of the heat to raising the temperature of the contiguous fabric and padding. As the furniture materials become warmer, they can undergo a phase change to a liquid (as do many thermoplastics), endothermically release adsorbed water (as do cellulosics), and/or or decompose to form other volatiles and a residual char. They also conductively transfer heat away from the hot spot under the cigarette coal. An ignition only occurs when the heat loss out from the cigarette locale is overwhelmed by the cigarette's burning rate.

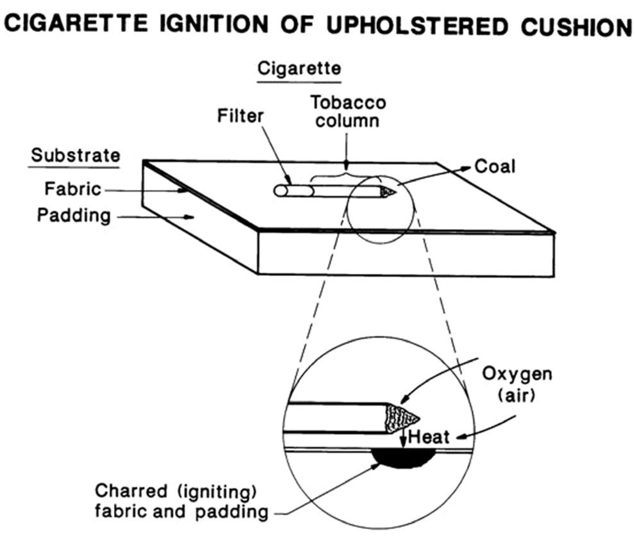

FIGURE 1 Schematic of the Interaction between a lit cigarette and a soft furnishing item

Laboratory research has led to multiple bench-scale test methods for RUF composites that capture this ignition process. They have been published by:

- ASTM International (ASTM E1352[11]);
- The National Fire Protection Association, NFPA (NFPA 261[12]); and
- The California Bureau of Household Goods and Services, BHGS (TB 116[13]).

None of these is mandated in regulation.

There are also multiple bench-scale test methods for RUF components published by:

- ASTM International (ASTM E1353[14]).
- The National Fire Protection Association, NFPA (NFPA 260[15]).
- The California Bureau of Household Goods and Services, BHGS (TB 117-1986[16] and TB 117-2013[17]). The latter is the basis for the only current regulation of residential furniture components in the U.S.
- The Upholstered Furniture Action Council, UFAC. This is a widely used, but voluntary, test for upholstery fabrics.

The test apparatus in each of these component tests is a small (approximately 20 cm in height width, and depth) furniture mock-up of an upholstered chair, as shown generically in Figure 2.

There are varying criteria for whether ignition of the mock-up has occurred. These include the spread of char along the horizontal cushion, the spread of char up the vertical cushion, mass loss of the assembly, visual inspection of the assembly, and the appearance of flames.

There is a Federal standard for the cigarette ignition resistance (CIR) of mattresses and mattress pads. Promulgated by the CPSC, 16 CFR Part 1632[18] involves placing nine lit cigarettes on various locations on the top surface of a mattress. A second set of nine cigarettes is placed similarly, but with cotton sheeting placed under and over the cigarettes. Failure is defined as visible charring spreading more than 2 in. (51 mm) from the cigarette.

In 1976, the National Bureau of Standards (NBS; now the National Institute of Standards and Technology, NIST), had determined that an unfiltered king-size Pall Mall[ii] was the strongest igniting commercial cigarette.[19] This became the de facto ignition source in all the above tests. It was specified by its mass and dimensions; there was no specification for ignition strength.

The use of the unfiltered Pall Mall was based on a simple principle. If soft furnishings and their components resisted ignition by the

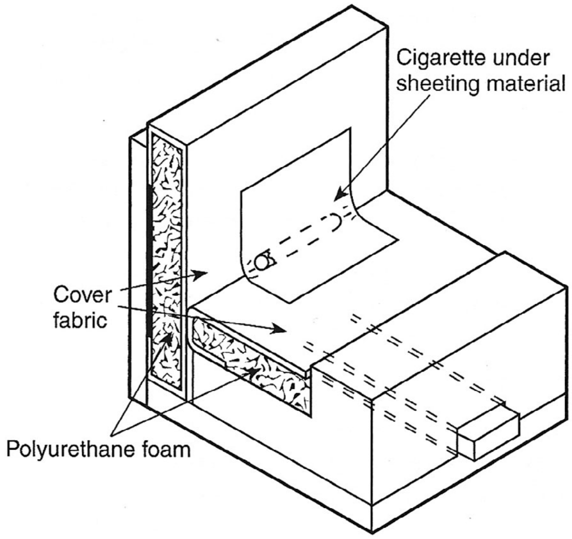

FIGURE 2 Diagram of apparatus for determining the ignition resistance of upholstered furniture mock-up components

TABLE 1 Changes in cigarette-initiated residential fires and the resulting fire losses between 1980 and 2003

Year	Reported Fires	Deaths	Injuries
1980	70 800	1820	4190
2003	18 300	690	1320

strongest commercial cigarette, then the soft furnishings should be less readily ignited by the other, weaker commercial cigarettes.

Coincident with the implementation of this testing was the increasing use of residential smoke alarms. Combined, these two advances in fire safety (and perhaps other factors) resulted in the substantial changes in residential fires and fire losses from cigarette-ignited fires shown in Table 1.[9] The year 1980 is the first year for which these fire loss data were compiled; 2003 was the last full year before a substantive change in cigarettes occurred (discussed below).

2 | THE ADVENT OF LESS FIRE-PRONE CIGARETTES

Recognition of the significant fire hazard posed by lit cigarettes dates back to at least the late 1880s, as indicated by the issuance of approximately 100 U.S. patents for less fire-prone cigarettes (also optimistically called “fire-safe cigarettes”) since then.[20] However, realizing such cigarettes on a commercial scale was forestalled by three limitations:

- The powerful tobacco industry was reluctant to support regulation. Information regarding the extent of health effects of smoking was emerging, and the tobacco industry was resistant to any form of regulation of its products.
- There was no test method for measuring the extent to which a cigarette was likely, or less likely, to start a fire.
- It was not clear that such a cigarette would be embraced by smokers. If not, as with liquor prohibition, a black market might arise, defeating the purpose of any regulation.

Spurred by a fatal cigarette-initiated fire in his District, U.S. Congressman Joseph Moakley of Massachusetts led the authorization for two Federal studies of the potential for the creation and requirement of less fire-prone cigarettes.[iii]

The first study was created under P.L. 98-567, the Cigarette Safety Act of 1984, and spanned 1984 through 1987. It commissioned a Technical Study Group (TSG) to “conduct activities 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 and mattresses.” The TSG efforts led to the following conclusion: “The Technical Study Group finds 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. Furthermore, the overall impact on other aspects of the United States society and economy may be minimal. Thus, it may be possible to solve this problem at costs that are less than the potential benefits, assuming the commercial feasibility of the modified cigarettes.[21]”

The second study was created under P.L. 101-352, the Fire Safe Cigarette Act of 1990 and spanned 1990 through 1993. It directed NIST and CPSC “to carry out research designed to provide an assessment of the practicality of developing a performance standard to reduce cigarette ignition propensity, that is, the likelihood that a cigarette will act as an ignition source for mattresses, upholstered furniture, and similar items.” Two of the charges to NIST were to develop a standard test method for measuring cigarette ignition propensity and to test a selection of commercial cigarettes.[22] These tasks resulted in the development of two test methods for the ignition propensity of cigarettes. The Mock-up Ignition Test Method involved placing a lit cigarette on an upholstered (standard fabric over specified foam) cushion and observing whether smoldering spread over the cushion more than 50 mm away from the cigarette. Both methods were correlated with laboratory tests of mock-ups of varying composition. The Mock-up Ignition Test Method was later discarded because the “standard” fabrics used in the method's development ceased to be available commercially and could not be reproduced on a practical and cost-effective scale. The Cigarette Extinction Test Method is discussed below. While NIST, the cigarette industry, and others continued research on less fire-prone cigarettes, little happened of note for the next 7 years.

In 2000, Philip Morris USA test marketed a version of their Merit cigarettes in four cities. These cigarettes used circumferential bands of cellulose applied to the paper that wrapped the tobacco column (Figure 3). This design followed one of five patented concepts tested

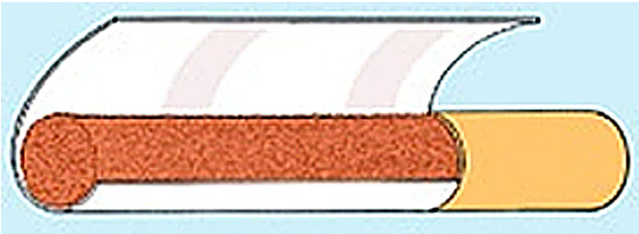

FIGURE 3 Schematic of a banded cigarette

under the Cigarette Safety Act of 1984[23] and shown effective at reducing cigarette ignition propensity.

Using the TSG Mock-up Ignition Test Method and the Cigarette Extinction Test Method, NIST found that conventional cigarettes produced 100% ignitions or full-length burns on five of the six test substrates. The test market Merit cigarettes had substantially fewer ignitions or full-length burns on all substrates.[24] Philip Morris revealed that there were some concerns from smokers during the test marketing. However, the results demonstrated the practicality of making such a cigarette with encouraging consumer acceptance.

Later that year, New York State Assemblyman Alexander Grannis, who had long been a proponent for regulating the safety of cigarettes, guided a bill through the State of New York requiring the Office of Fire Prevention and Control to promulgate fire safety standards for cigarettes sold or offered for sale in New York State. These standards were to ensure that such cigarettes, if ignited, would stop burning within a specified time of not being smoked or that such cigarettes would meet performance standards to limit the risk that such cigarettes would ignite upholstered furniture, mattresses or other household furnishings. This would lead to the first regulation of cigarettes of any type and the first requirement for cigarette fire safety. NIST promptly contacted the OFPC, offering expertise to help develop the performance test method for such a standard.[iv] The offer was accepted.

The test method developed by NIST was derived from the Cigarette Extinction Test Method. It was processed and published by ASTM as ASTM E2187-02a[25]). The 2004 version (ASTM E2187-04[26]) contained revisions that did not affect the basic nature of the test method.[v]

A simplified description of the test method is as follows. A lit cigarette is placed on a standard substrate. The substrate absorbs some of the heat generated by the cigarette, reducing the heat available to keep the cigarette burning. A test comprises 40 determinations. The test output is the fraction of cigarettes that burned the length of the tobacco column. Multiplying this fraction by 100 gives a commonly used alternative representation—percentage of full-length burns, PFLB. The ASTM standard contained three standard substrates—3, 10, and 15 layers of Whatman No. 2 filter paper. This brand was specified because (a) this was the most common brand of filter paper in the U.S. at the time, (b) its composition was essentially 100% cellulose, and (c) the mass of the paper sheets was quite uniform. The test apparatus, enclosed in a draft-free housing, is shown in Figure 4. Figure 5 shows some typical test results.

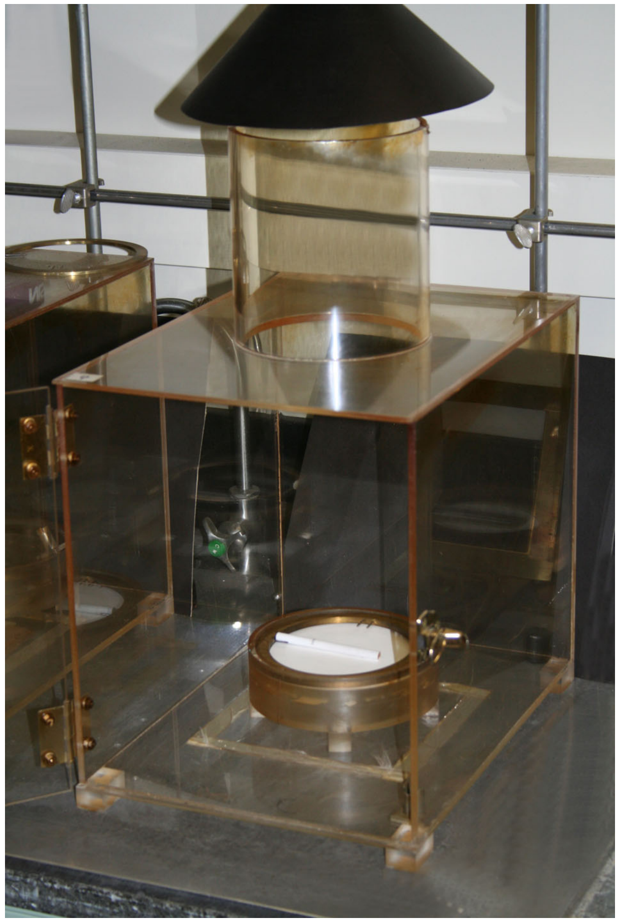

FIGURE 4 Photograph of the test apparatus in ASTM E2187-04 (NIST photograph)

FIGURE 5 Photograph of typical results of determinations using ASTM E 2187-04 (NIST photograph). Top: full-length burn of a non-filter cigarette; Right: full-length burn of a filter cigarette; Left: ceased burning of a less fire-prone cigarette

The New York State Rule was effective June 28, 2004.[27] It cited ASTM E2187-02a with modifications that made it identical to ASTM E2187-04. The required substrate was 10 layers of Whatman

No. 2 filter paper, and the performance requirement was that no more than 10 of the 40 determinations may result in a full-length burn. For cigarettes that were banded, there were requirements to ensure that there were at least two bands along the tobacco column. Manufacturers were to institute and maintain a quality control program, with a prescribed maximum degree of variability in the test results. A manufacturer was required to certify that each cigarette met the standard, with recertification due every 3 years. Each pack and carton had to be marked to indicate compliance with the standard.

With support from the Coalition for Fire-safe Cigarettes, led by the NFPA, within 7 years the other 49 States, the District of Columbia, and Canada had implemented regulations that were substantively the same as the New York rule. They agreed that the pack and carton marking would be the three letters “FSC,” standing for Fire Standard Compliant.

3 | THE FIRST STANDARD REFERENCE CIGARETTE, SRM 1082

3.1 | Initial issuance

Two states, first New York and then Massachusetts, announced they would conduct compliance testing of all brand-styles, over 1000 in all, of cigarettes sold in their States. It was also possible that other organizations might perform some brand-style testing. Thus, manufacturers needed to be confident that a compliant cigarette design would be recognized as such by other test laboratories. Alternately worded, all laboratories performing tests needed confidence that they were obtaining the same result for each brand-style.

To resolve this, NIST offered to issue a Standard Reference Material, SRM®.[28] The advantages of using an SRM cigarette were that:

- There would be a supply of uniform cigarettes over an extended period of time. Previously, there was no assurance that, with the evolutionary changes in cigarette formulation for non-fire-related reasons, a commercial cigarette would retain its initial ignition strength.
- Cigarette developers and regulators would include it in both their testing, and in their quality assurance and quality control test programs.
- The certified performance of the SRM cigarette using ASTM E2187 would be in the PFLB range expected of future commercial cigarettes. While all the regulations required that an FSC cigarette have no more than 25 PFLB, a practical design objective for the manufacturers was significantly lower.
- This performance would be well documented.

The proposal was accepted, and NIST designated this cigarette as SRM 1082.

The performance specification for the SRM was developed as follows. Following discussions with manufacturers and regulators, NIST issued a Request for Proposals for cigarettes of about half this PFLB criterion. The physical properties of the cigarettes would be typical of filter-tip king-size cigarettes. A contract was awarded to Philip Morris USA for 5000 cartons (1 million cigarettes), with the cartons to be numbered in the order of manufacture. After a series of prototypes was tested, a design was reached for a test cigarette with the proper PFLB. The cigarette had a filter tip and was filled with expanded tobacco, features which the TSG study had shown favored low ignition propensity.[23] The nominal properties of the cigarettes were:

- Length: 100 mm
- Circumference: 25 mm
- Mass: 0.58 g
- Tobacco: 100% expanded Bright
- Paper porosity: 52 CORESTA units

The certification of SRM 1082 cigarettes was accomplished as follows. Upon arrival at NIST in April 2005, packs from 40 cartons were selected at random for testing according to ASTM E2187-04. The testing was conducted by NIST, the National Research Council of Canada, and Kidde-Fenwal's Combustion Research Center. (Canada had passed legislation requiring that only FSC cigarettes be sold in that country. Kidde-Fenwal was the contractor selected by New York State for their brand-style certification testing.) The test operators in all three laboratories had been trained in the test method and had already obtained consistent results on other cigarettes. In all, 30 tests comprising 1200 determinations of SRM 1082 cigarettes were performed.

The certified value and its uncertainty were obtained by fitting a Bayesian hierarchical model[29] to the data from the three laboratories. The model accounted for random variation both within and between laboratories. The data from each laboratory were modeled using individual binomial likelihood functions, the between-laboratory variation was modeled using a beta distribution, and non-informative prior distributions were used for all parameters in the model. The model was fit to the data using Markov chain Monte Carlo methods.

The certified value and expanded uncertainty (reported at the 95% probability level) was (12.6 ± 3.3) PFLB.[30] This uncertainty included measurement variability within and between laboratories. Tests for cigarette uniformity did not show evidence of any significant variation in ignition strength among the packs.

It is NIST policy that the certification of an SRM have a fixed lifetime. The initial choice of lifetime is based on any information about the shelf life, or stability, of the SRM material(s).

Commercial cigarettes normally are manufactured, sold, and smoked in a matter of months. An SRM supply limited by this duration would negate much of the value of a Standard Reference cigarette. In 2003, NIST had examined measurements of the ignition strength of some experimental cigarettes since their manufacture in 1992 under the Fire Safe Cigarette Act of 1990.[22,31] The cigarettes, numbered 501 through 532, had been stored in freezers since then, and the measurements had been performed between 1992 and 2003. As

TABLE 2 Summary of ignition strength measurements (PFLB and standard error)

Laboratory	Protocol	Cigarette Type/Layers of Filter Paper		
		529/3	516/10	532/15
ILE (1993)[a]	1993[a]	57 ± 9	—	—
NIST (2001)	E2187-02b precursor	66 ± 13	34 ± 13	82 ± 10
NIST (2002)	E2187-02b	78 ± 10	21 ± 10	67 ± 11
Kidde-Fenwal (2002-03)	E2187-02b	58 ± 12	22 ± 10	71 ± 10
National Research Council of Canada (2003)	E2187-02b	—	25 ± 10	—

[a]ILE: a nine-laboratory evaluation of the cigarette extinction method.[22] The report date is 1993; the testing was performed in 1992.

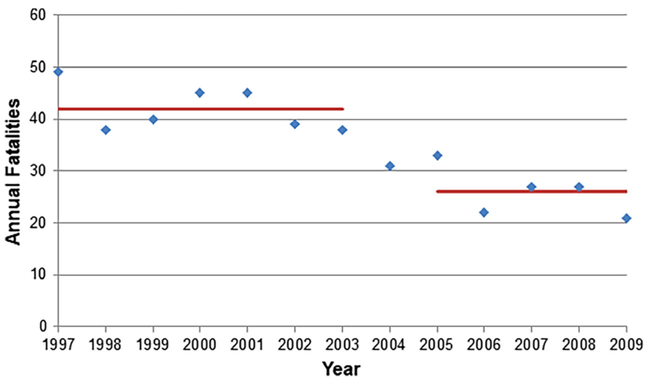

FIGURE 6 Reported fatalities from cigarette-initiated fires in the state of New York by year

shown in Table 2, there was no statistically significant difference among the measured ignition strengths and the standard errors over that period. The conclusion was that the ignition strength of a cigarette should be stable for 10 years when properly stored.

Based on this finding, the initial expiration date of the SRM 1082 certification was set at December 31, 2015, nominally 10 years after the cigarettes' manufacture.

The remainder of the 5000 cartons were stored in a chiller at −18°C (0°F), as required in the ASTM standard. NIST would perform periodic testing to verify that the cigarettes continued to produce the same test result. Sales of SRM 1082 cigarettes began in February 2006.

In December 2010, the European Union announced a regulation substantively the same as those in North America. It cited ISO 12863,[32] a clone of ASTM E2187-09. Soon, there was substantial demand for SRM 1082 cigarettes worldwide, and sales of the SRM 1082 cigarettes reached approximately 300 cartons per year.

U.S. fire loss data in the years following the FSC regulations demonstrated their impact. Compiled data from the State of New York showed a reduction of ca. 40% in fatalities from cigarette-initiated fires (Figure 6). The numbers of fatalities are from the NFPA web site.[33] The mean number of annual fatalities and their standard errors are (42 ± 2) and (26 ± 3) for the years before and after the implementation of the Rule, respectively. Our horizontal lines represent these mean values. The decrease in annual fatalities is approximately 40%.

Additional analyses of changes in the number of fires and in fire losses followed. Alpert and co-workers found that the Massachusetts law decreased the likelihood of unintentional residential fires caused by cigarettes by 28% between 2004 and 2010.[34] Butry and Thomas found a 45% reduction nationally in cigarette-initiated RUF fires and a 23% reduction in deaths from those fires between 2002 and 2011.[35] Hall found a 30% reduction in U.S. fire deaths from all cigarette-initiated fires between 2003 and 2011.[9] Each of these used the NFIRS database, but with differing methods of analysis. Yau and Marshall used the National Center for Health Statistics mortality data. They found a 20% reduction in U.S. fire deaths between 2000 and 2010, with some State-to-State variation.[36] (These authors noted that most States implemented FSC legislation during or after 2009, which hampered the full application of their model.)

Overall, there was an approximate 30% reduction in reported fatalities from cigarette-initiated fires resulting from the regulations. From 1999 to 2003, the average number of fatalities from these fires was approximately 750.[9] Thus, the requirements for FSC cigarettes resulted in approximately 200 lives being saved annually nationwide.

The use of SRM 1082 cigarettes played a key role in this improvement in life safety by assuring the accuracy of commercial cigarette testing using ASTM E2187.

3.2 | The first two re-certifications of SRM 1082

As 2015 approached, there was still a significant supply of these cigarettes remaining. Continued offering of the SRM 1082 cigarettes required that the expiration date be extended. However, this was not to be a straightforward process—the Whatman No. 2 filter paper had changed, and the change affected the performance of cigarettes in ASTM E2187.

The demand for Whatman No. 2 filter paper for cigarette testing had sharply increased the sales of the product. In about 2011, Whatman (now a Division of GE Healthcare) moved the manufacture of its No. 2 filter paper from the United Kingdom to a larger plant in China. While the paper from this plant was apparently functioning acceptably for filtration, routine testing indicated that the Chinese paper was giving very low values of ignition strength in ASTM E2187. This was later confirmed in an ILE,[37] with the mean value of the ignition strength of SRM 1082 cigarettes found to be (5.0 ± 1.5) using

10 sheets of China Whatman filter paper and (13.6 ± 3.2) PFLB using the metal/paper substrate described below. Recall that the certified value using the U.K. paper was (12.6 ± 3.3) PFLB.[vi]

A 2009 ILE had examined whether other brands of filter paper might be equivalent to the original Whatman paper manufactured in the U.K..[38] The results for a small number of cigarette types indicated some higher and some lower ignition strength results for some cigarette/paper combinations. Thus, tests of a much larger set of cigarettes would be needed to demonstrate equivalency of a particular brand of paper to Whatman No. 2 made in the U.K. It was also not clear how to adjust the formulation or processing of a particular paper to achieve the equivalent results.

With these results in mind, NIST started research to develop an alternate type of substrate for ASTM E2187. A successful candidate would be:

- minimally dependent on a natural product,
- readily fabricated or assuredly available into the future,
- precise in its thermal and physical properties,
- safe to use,
- consistent in its contact with the test cigarette, and
- usable for repeat tests, if it were expensive.

Its use would also result in ignition strength values that were the same as, or relatable to, those obtained with Whatman No.2 paper made in the U.K.

SRM 1082 and the modest supply of experimental cigarettes from the Fire Safe Cigarette Act of 1990 would be the principal links between the Whatman No. 2 substrate and the new substrate.

A wide range of organic and inorganic materials were examined,[39] including some that had been studied in developing the original filter paper substrates. The optimal candidate was a sheet of 302 stainless steel shim stock with a single sheet of filter paper on the top. The shim stock is a precisely specified alloy with a uniform specific heat and a thickness of (0.203 ± 0.004) mm. It is one of several used as a spacer in a variety of industries and is thus likely to be commercially available long-term. It has a long shelf life and thus could be stockpiled if its longevity in commerce became questionable. It is available as a nearly flat sheet and can be flattened further. It is quickly cleanable with conventional organic solvents and thus can be used for multiple tests.

One of the combustion products from a burning cigarette is water vapor. During tests on the bare steel, this condensed on the metal surface and "drowned" the cigarette. This was not the intended extinguishment in the test. A single sheet of filter paper placed on top of the metal shim absorbed and spread the moisture away from the zone near the cigarette coal.

NIST testing in 2013[39] found that the ignition strength values were not sensitive to the manufacturer of the steel, as shown in Table 3. The filter paper used in this work, both as the 10-sheet substrate and as a single sheet over the steel shim stock, was U.K. Whatman No. 2.

For each cigarette, the mean values are not significantly different from each other. The mean values and uncertainties for SRM 1082 are also not significantly different from the value and uncertainty on the original certificate.[vii] The calculated uncertainties for the metal/paper substrate might be smaller than for the all-paper substrate, perhaps due to the single interlayer contact surface in the steel/paper substrate, compared to nine in the all-paper substrate.

Because of the similarity in ignition strength values between the paper and steel/paper substrates shown in Table 3 and because there was no evidence that the ignition strength of the SRM 1082 cigarettes had changed, the certificate was renewed with the original value and 95% confidence interval. The new expiration date was set as December 31, 2017.

Later testing established a specification for the thickness of the steel,[37] and further, unpublished work established specifications for the mass range and moisture content of the filter paper. The new substrate and these specifications have been incorporated into ASTM E-2187-16.[40] This established the test method that would be the basis for future SRM 1082 recertification.

Late in 2017, a second re-certification was needed. This was because the cigarettes were still in demand, and a multi-year supply remained.

To re-affirm that the SRM 1082 cigarettes had not changed ignition strength in the four years since the 2013 testing, NIST tested them on five batches of stainless steel shims and two types of filter paper. The data are presented in Table 4.[41] Paper A was taken from a retained supply of one of the brands that had performed similar to U.K. Whatman No.2 paper in Reference 38. The second paper (W) is Whatman No.2 filter paper manufactured in China.

These data indicate that the measured ignition strength of the SRM cigarettes had not changed significantly despite the storage for 12 years and the use of a different test substrate. Specifically, the overall PFLB value is statistically indistinguishable from both the original certified value and the values shown in Table 3. Furthermore, there was no significant difference among the various combinations of metal and paper in the substrates.

The certification was extended to June 30, 2019, retaining the original mean value and uncertainty.

TABLE 3 Mean PFLB values and uncertainties (95% probability level) for substrates of 10 layers of filter paper and each of three shim stocks with a single layer of paper

	PFLB values			
Cigarette Design	**Paper**	**Metal 1**	**Metal 2**	**Metal 3**
SRM 1082	14.6 ± 7.6	13.6 ± 5.3	15.4 ± 5.8	16.1 ± 5.8
2	30.5 ± 9.9	22.9 ± 6.5	27.8 ± 6.9	20.4 ± 6.2
3	10.9 ± 6.9	7.4 ± 4.1	5.6 ± 3.6	4.9 ± 3.4

TABLE 4 Summary of mean PFLB values and uncertainties (calculated at the 95% probability level) for the 2017 Re-certification of SRM 1082 Cigarettes determined using ASTM E2187-16

Shim No.	Paper	Number of determinations	Measured FLB	Calculated PFLB value and 95% confidence interval
1	A	100	13	13.0 (7.2 to 21.2)
2	A	100	22	22.0 (14.3 to 31.4)
3	A	60	14	23.3 (13.4 to 36.0)
4	W	100	12	12.0 (6.4 to 20.0)
4	A	100	9	9.0 (4.2 to 26.4)
5	A	60	9	15.0 (7.1 to 26.6)
Overall result:		520	79	15.2 (12.9 to 17.5)

TABLE 5 Summary of the ignition strength and 95% confidence intervals (C.I.) for the 2019 Re-certification of SRM 1082 Cigarettes on metal/paper substrates

Test[a]	Year	Carton Number[b]	Determi-nations	# of FLB	PFLB	Lower 95% C.I., PFLB	Upper 95% C.I., PFLB
1	2013	NA	240	36	15.0	10.7	20.2
2	2016	NA	100	12	12.0	6.4	20.0
3	2016	NA	100	15	15.0	8.6	23.5
4	2016	NA	100	29	29.0	20.4	38.9
5	2019	908	42	5	11.9	4.0	25.6
6	2019	1243	49	5	10.2	3.4	22.2
7	2019	1253	43	4	9.3	3.6	22.1
8	2019	1543	38	5	13.2	4.4	28.1
9	2019	1673	43	7	16.3	6.8	30.7
10	2019	1718	53	7	13.2	5.5	25.3
11	2019	1743	31	4	12.9	3.6	29.8
12	2019	2333	22	3	13.6	2.9	34.9
13	2019	2618	68	10	14.7	7.3	25.4
14	2019	3158	62	12	19.4	10.4	31.4

[a]The Test 1 entry is from Reference 39. The Test 2 through 4 entries are NIST data (Lab #5) from Reference 37. The substrates were: Test 2—a sheet of 302 stainless steel covered by one sheet of China Whatman No.2 filter paper, Test 3—a different sheet of 302 stainless steel covered by one sheet of U.K. Whatman No.2 filter paper; Test 4—a third sheet of 302 stainless steel covered by one sheet of U.K. Whatman No.2 filter paper. All the 2019 data are from Reference 41 and were obtained by a test operator different from the operator in Reference 37.
[b]At the time of this analysis, carton numbers were not available for the 2013 and 2016 data. The analysis acts as though each of the first four Tests corresponds to a single, unique carton.

3.3 | The final recertification of SRM 1082

3.3.1 | Approach

Rather than continue a possible series of short-term extensions of the SRM 1082 certification, NIST decided to develop the information needed to extend the certification for the remainder of the supply of cigarettes, which was estimated to be approximately 7 years. There were two tasks to be performed.

- Generation of data to support a forward-looking PFLB value and uncertainty using the steel/paper substrate in ASTM E2187-16.
- Derivation of a sound basis for an expiration date that would encompass the sales duration of the remainder of the cartons.

3.3.2 | Determination of the ignition strength and its uncertainty

To address the first task, NIST performed new tests using steel/paper substrates.[41] The results from these tests, combined with the output from prior results using steel/paper substrates, and comprising a total of 991 determinations are compiled in Table 5.

In Table 5, the data referred to as tests 2, 3, and 4 were collected as part of an interlaboratory study, in which six labs besides NIST also conducted tests on SRM 1082 cigarettes. Each round of testing used a different combination of steel shim manufacturer and filter paper manufacturer, and within each round, the same combination of filter paper and steel shim providers was used by all participating laboratories. The increased PFLB observed for NIST in "Test 4" was not consistently replicated by other participating laboratories, so NIST scientists do not believe that these data reflect a bias due to manufacturer. The analysis in this report treats the data from "Test 4" in the same way as all the other data. In Tests 5 through 14, a single operator selected cigarettes at random from 10 cartons, recording the carton identification for each determination. The testing used four steel rectangles from a single manufacturer.

In the statistical analysis of the data provided in Table 5, the PFLB values and their respective confidence interval[viii] bounds were converted to proportions (using = PFLB/100) and transformed onto the logit scale (ie, the function $logit(x) = \log\left(\frac{x}{1-x}\right)$, which maps the [0,1] interval to the whole real line). For each row in Table 5, this produced a corresponding $\text{logit}\left(\frac{\text{PFLB}}{100}\right)$ as well as upper and lower confidence limits (referred to as $\text{upper logit}\left(\frac{\text{PFLB}}{100}\right)$ and $\text{lower logit}\left(\frac{\text{PFLB}}{100}\right)$, respectively). An approximate SE for each $\text{logit}\left(\frac{\text{PFLB}}{100}\right)$ value was computed as:

$$\text{Std . Error logit}\left(\frac{\text{PFLB}}{100}\right) = \frac{\text{upper logit}\left(\frac{\text{PFLB}}{100}\right) - \text{lower logit}\left(\frac{\text{PFLB}}{100}\right)}{4},$$

where the 4 comes from the fact that, for a normal distribution, a 95% confidence interval spans roughly 4 standard errors.

The values of $\text{logit}\left(\frac{\text{PFLB}}{100}\right)$ and $\text{Std.Error logit}\left(\frac{\text{PFLB}}{100}\right)$ were entered as measured values and standard uncertainties, respectively, in the NIST Consensus Builder.[42] The NIST Consensus Builder was used to conduct a DerSimonian-Laird analysis with the Knapp and Hartung adjustment, which provided the following results:

The consensus estimate for average $\text{logit}\left(\frac{\text{PFLB}}{100}\right)$ is −1.68.

The standard uncertainty for average $\text{logit}\left(\frac{\text{PFLB}}{100}\right)$ is 0.111.

The 95% coverage interval for average $\text{logit}\left(\frac{\text{PFLB}}{100}\right)$ ranges from −1.91 to −1.43.

The dark uncertainty (tau) is 0.177.

The result from the DerSimonian-Laird analysis that dark uncertainty (tau) is estimated as 0.177 indicates a statistically significant variability among the testing results across cartons. That is, the level of variability in the results across cartons exceeds what can reasonably be expected from randomness of binomial behavior with a common ignition strength across all tests. Following the guidelines of NIST SP 260-136,[43] a combined uncertainty that includes the observed level carton-to-carton variability was computed as $u_c = \sqrt{u(\mu)^2 + \tau^2} = \sqrt{0.111^2 + 0.177^2} = 0.209a$. Using k = 2.16, the 97.5th percentile from a t-distribution with 13 degrees of freedom, an expanded uncertainty was computed as $2.16 * u_c = 0.451$. A 95% prediction interval corresponding to the expected $\text{logit}\left(\frac{\text{PFLB}}{100}\right)$ of a single randomly sampled carton of SRM 1082 cigarettes was computed as -1.67 ± 0.54. Note that this interval corresponds to the 0.025 and 0.975 quantiles of the predictive distribution (ie, the central 95%). The values of the estimate and the bounds of the 95% prediction interval were transformed back to the scale of ignition strength via the logistic function $f(x) = 100 * \frac{\exp(x)}{1+\exp(x)}$.

The resulting values were an estimated ignition strength of 15.8% with a corresponding expanded uncertainty interval of (10.8%, 22.7%). Note the logistic transformation is nonlinear and causes the uncertainty interval that was symmetric around the estimated value on the logit scale to become asymmetric on the ignition strength scale. Due to the asymmetry of this interval, the interval was recalculated using the 0.01 and 0.96 percentiles of the predictive distribution on the logit scale, −2.22 and − 1.27, respectively. This was then transformed back to the scale of ignition strength via the logistic function giving the midpoint and (symmetric) expanded uncertainty.

Figure 7 is a plot of the 14 testing results from Table 5 and their reported uncertainties, along with the evaluated consensus estimate and corresponding uncertainty estimates.

The new certified value is (15.7 ± 6.6) PFLB.[44] This is based on determinations using a substrate of 302 stainless steel shim stock with one sheet of filter paper, as specified in ASTM E2187-16. The expanded uncertainty interval is intended to represent the symmetric range within which NIST would expect the ignition strength of a single randomly selected carton of SRM 1082 cigarettes to fall with 95% confidence when tested at the NIST laboratory by a trained NIST scientist.

3.3.3 | Possible error introduced by repetitive use of the stainless steel

The Interlaboratory Evaluation of the steel/paper substrate[37] had indicated a high degree of data scatter among the laboratories with some of the metal/paper substrates. Guindos et al recently suggested that heating and cooling during repetitive use of the stainless steel shim might lead to changes in the metal, resulting in progressively enlarged variability in test results.[45] It was thus important to establish an extent to which the steel could be re-used without significantly affecting the test results.

NIST performed over 100 ASTM E2187-16 determinations of the ignition strength of SRM 1082 cigarettes using each of four pieces of shim stock, as well as a small number of determinations on five other pieces of shim stock (from largest to smallest the number of determinations for each of the nine pieces of shim stock were 106, 105, 105, 100, 8, 7, 7, 7, and 6). Quantitative analysis of the PFLB test results involved binning by how many times the piece of shim stock had previously been used, in groups of 20. Bin "0-19," corresponded to determinations that were among the first 20 to take place on a given substrate, followed by bins "20-39," "40-59," "60-79," and "80 + ." The data for each bin are reported in Table 6 below.

The null hypothesis that each bin has the same long-run PFLB was tested by applying Fisher's exact test to the FLB and non-FLB counts in Table 6, which resulted in a *P*-value of 0.589. This result indicates that these data do not provide convincing evidence of differences in long-run PFLB among the considered bins. Note that this does not imply that the data show that there are absolutely no differences. Comparing the 95% confidence intervals for each respective bin, as seen in Figure 8, still allows for the possibility of substantial differences among the PFLB of each bin. However, these results do not show evidence of a trend either in the magnitude of or variability in the measured ignition strength.

To complement these test results, after each determination, the researchers qualitatively compared the stainless steel shim

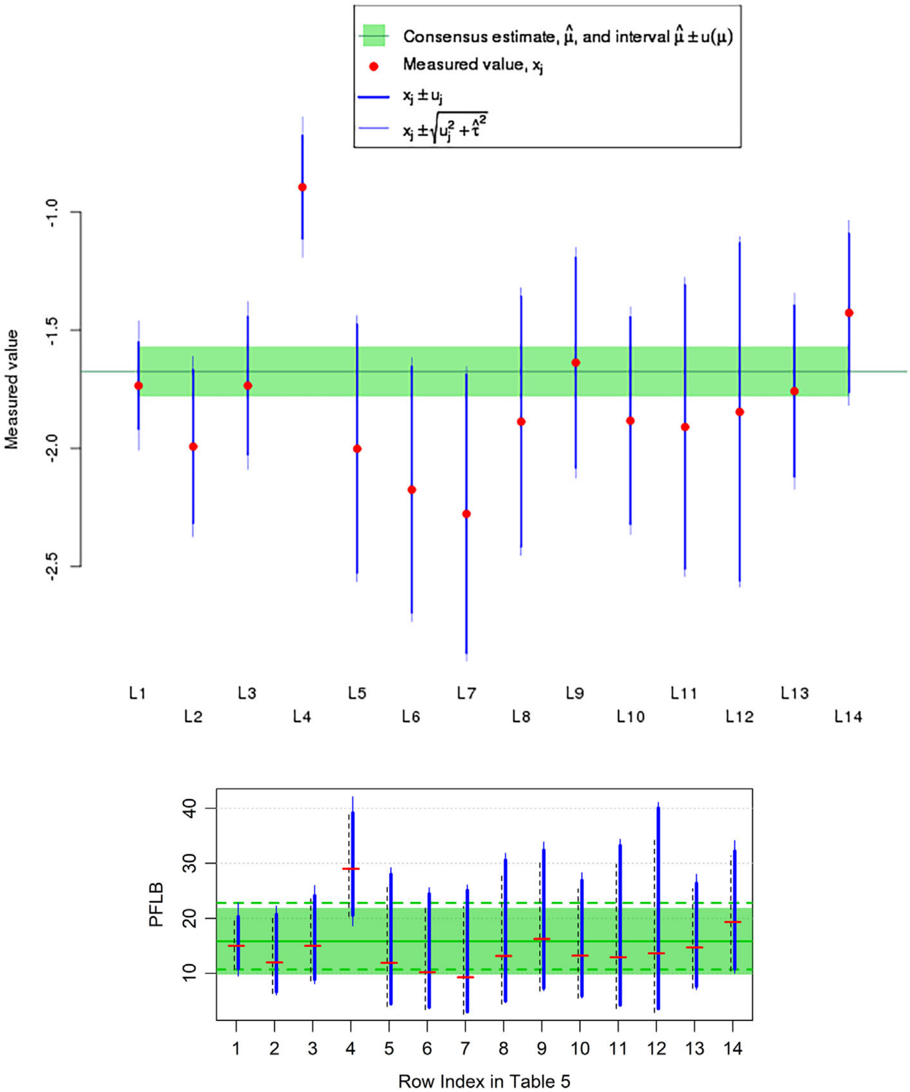

FIGURE 7 NIST ignition strength test results (ASTM E2187-16[5]) for cigarettes tested on stainless steel shim stock and one layer of filter paper and the corresponding consensus interval estimated via DerSimonian-Laird analysis. The solid, dark green, horizontal line depicts the consensus PFLB estimate of 15.8% and the light green strip depicts the corresponding 95% uncertainty interval of 9.9% to 21.8%. The dashed green horizontal lines depict the symmetric 95% uncertainty interval of 10.7% to 22.8%. The red horizontal line segments depict the individual PFLB values reported in Table 5 and the dashed vertical lines depict the corresponding 95% confidence intervals. The thick blue vertical lines reflect the logit scale uncertainty characterization used as inputs to the consensus builder and the thin blue lines reflect the uncertainties after including the estimated dark uncertainty

TABLE 6 NIST ignition strength test results for SRM 1082 for use in establishing the durability of the steel/paper substrate in ASTM E2187-16

Bin label	Determinations	# of FLB	# of non-FLB	PFLB	Lower 95% C.I., PFLB	Upper 95% C.I., PFLB
0-19	115	15	100	13.0	7.5	20.6
20-39	80	10	70	12.5	6.2	21.8
40-59	80	15	65	18.8	10.9	29.0
60-79	80	8	72	10.0	4.4	18.8
80+	96	14	82	14.6	8.2	23.3

used in the determination with stainless a steel shim that had never been used in testing. This included visual inspection, response and feel when flexed in and perpendicular to test direction, and concavity. The researchers reported no observable difference between the untested and tested stainless steel substrates at any point during the approximately 100 determinations in each substrate series.[41]

In view of these test results, ASTM E2187-20[46] allows the use of a piece of shim stock for as many as 80 determinations, which is the number of determinations in two tests. As more data become available, this limit can be increased.

3.3.4 | Establishment of the duration of the re-certification

Based on the current stock of SRM 1082 cigarettes and assuming sales would continue at the current rate, the supply of cigarettes

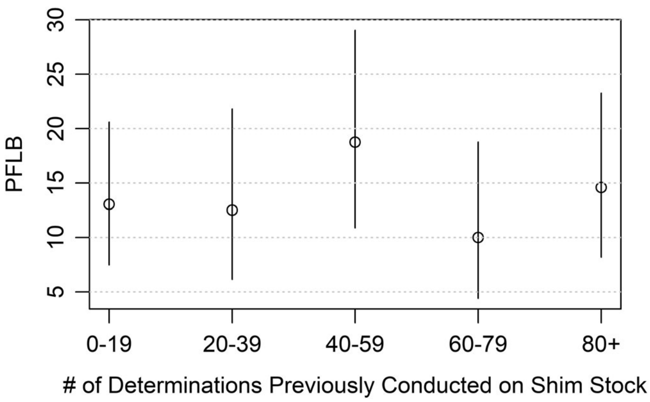

FIGURE 8 NIST ignition strength test results (ASTM E2187-16[5]) for cigarettes tested on stainless steel shim stock and one layer of filter paper grouped by number of determinations previously conducted on shim stock

should be depleted by 2025. NIST examined the potential for this certification to be supportable for at least that long.

The SRM 1082 cigarettes were manufactured in 2005 and stored in a chiller at −18°C (0 °F), as required in the ASTM standard. The data presented above indicate that the ignition strength of the cigarettes had been stable through 2019, that is, for 14 years. The following describes how NIST established confidence that this stability would last at least another 6 years.

In early 1992, the cigarette industry had manufactured a set of experimental cigarettes for testing under the Fire Safe Cigarette Act of 1990.[22] As mentioned earlier, NIST retained some of these for possible future research in implementing the output of the 1990 Act. Table 2 showed that ignition strength for three of these cigarettes helped establish the initial SRM 1082 expiration date. Two of these were now used in establishing the final expiration date.

- Cigarette 529 is a 100 mm long, 25 mm circumference, filter tip cigarette, filled with expanded tobacco. These properties are similar to the SRM 1082 cigarettes. Table 2 shows that it did not change ignition strength from a year after its manufacture through the following 11 years.
- Cigarette 516 is a 100 mm long, 21 mm circumference, filter tip cigarette, filled with expanded tobacco. These properties are also similar to the SRM 1082 cigarettes, although the diameter is somewhat smaller. Table 2 shows its ignition strength was approximately 25 PFLB on 10 layers of U.K. Whatman No.2 filter paper.

Since these cigarettes are both fabricated from expanded tobacco and incorporated similar wrapping paper, it is reasonable to assume that the ignition strength of the 516 cigarettes had not changed since 1993 as well.

Cigarette 2 in Table 3 is Cigarette 516. In 2013, when tested on the all-paper (U.K. Whatman) substrate, its tested ignition strength was not significantly different from the 2002-2003 values.[39] Moreover, the test value was not significantly different from that using the steel/paper substrate. Combined with the stability of the 529 cigarettes, this indicates that the ignition strength of the 516 cigarettes was stable for 21 years and that its value was similar regardless of which of the two test substrates was used.

In 2019, NIST again measured the ignition strength of the 516 cigarettes using ASTM E2187-16, performing 120 determinations.[41] The result was (30 ± 8) PFLB, measured with the rough side facing upward, which is not statistically different from the earlier values.

Based on this research, NIST recertified SRM 1082 through June 30, 2027. This date is 2 years later than the anticipated depletion of the supply, yet is within the 26-year cigarette lifetime described above.

4 | CIGARETTE IGNITION RESISTANCE TESTING AND THE SECOND STANDARD REFERENCE CIGARETTE, SRM 1196

4.1 | The need

By 2008, enough of North America had enacted legislation requiring FSC cigarettes that many cigarette companies expressed support for *uniform* State regulations and announced they would begin converting production to FSC cigarettes nationwide. In particular, the R.J. Reynolds Tobacco Company, the manufacturers of the king-size, unfiltered Pall Mall (the commercial test cigarette, or CTC), announced that they would only make the FSC version.

This change in manufacturing had significant consequences for the testing of RUF and mattresses for CIR. No longer would there be a commercial cigarette with an ignition strength that was higher than most cigarettes being smoked. Over decades, this difference in ignition strength had led to improved fire safety of soft furnishings. A weaker test cigarette would allow more susceptible soft furnishings to enter the market, leading to an increase in fires and fire losses.

As a result, the result, NIST and CPSC pursued two efforts:

- Development of a second Standard Reference Material cigarette.
- Development of a Standard Ignition Source (SIS) that was not a tobacco-burning product.

4.2 | Issuance of SRM 1196

With the acceptance of SRM 1082 by the cigarette manufacturers and regulators, NIST followed a similar process to procure an SRM cigarette that would be comparable to the CTC.

The process began with acquiring pre-FSC versions of the CTC with varying years of manufacture. Combined, CPSC and NIST had five such versions that had been manufactured between 1992 and 2008.

Next came the creation of a test method to measure the ignition strengths of cigarettes with an ignition strength similar to that of the CTC. Following the principle at the heart of ASTM E2187, it should have been possible to replace the filter paper substrates (small heat sinks) with a substrate that would extract more heat from the lit cigarette. The rest of the test procedure would be used unchanged. After some experimentation, NIST found that testing on a nominally 6.3 mm (0.25 in.) thick brass plate plus a single sheet of filter paper[47] produced quantitative (ie, different from 0 PFLB and 100 PFLB) values of ignition strength for the five vintages of the CTC. The results of up to five sets of 40 determinations, using (the dwindling supply of) U.K. Whatman No. 2 filter paper, for each vintage are shown in Table 7.

These data indicated that the ignition strength of the CTC had been changing over time, presumably having little to do with its use as an ignition source for CIR testing. Discussions within the fire community led to a decision to model the SRM ignition strength and physical properties after the earliest CTC vintages.

As mentioned earlier, the CTC had been selected because it was the cigarette with the highest ignition propensity at the time. It was deemed valuable to gain some indication of the CTC performance relative to other recent commercial cigarettes. NIST tested packs of three commercial brand styles of cigarettes that had been purchased in 2007 and were not FSC. They were designated A, B, and C. Eighty determinations of each brand style were conducted, half with the rough side of the filter paper up, and the other half with the smooth side up. NIST also performed the same number of determinations for an FSC cigarette, designated D. The results of these tests are compiled in Table 8.

The measured ignition strengths of cigarettes A, B, and C were no higher than the ignition strengths of the 1992, 2001, and 2006 vintages of the CTC. As expected, none of the cigarette D determinations resulted in a full-length burn on this heavy substrate. These results confirmed that the use of a FSC cigarette design would not preserve the difference in ignition strength between commercial cigarettes and the CTC. It also showed that recent commercial designs could approach the ignition strength of the CTC.

The new standard cigarette would be designated SRM 1196. In 2009, NIST contacted the cigarette industry for proposals for the manufacture of this cigarette and again selected Philip Morris USA for the project. Philip Morris readily arrived at a formulation with an ignition strength comparable to the early vintages of the CTC, and NIST placed an order for 10 000 cartons (2 million cigarettes).

Upon their arrival in June 2010, 40 cartons were selected at random from the full supply. For the certification testing, NIST and the National Research Council of Canada performed a total of 270 tests for a total of 1080 determinations, using the substrate consisting of the brass plate and a single sheet of U.K. Whatman No. 2 filter paper.

The certified value and its uncertainty were obtained by fitting a Bayesian hierarchical model to the data using a binomial likelihood function and a flat, relatively non-informative prior distribution for the ignition strength of the cigarette. Tests for cigarette uniformity carried out by fitting a Bayesian hierarchical model to the data did not show evidence of any significant variation in ignition strength day-to-day or between cases, cartons, or packs.[48]

The expanded uncertainty was reported at the 95% probability level. Although the expanded uncertainty of the certified value was not computed using the methods outlined in the ISO Guide,[49] the results of the Bayesian analysis can be interpreted in essentially the same way as results from the ISO approach. The expanded uncertainty, U, can be expressed as $U = ku_c$, where u_c = 1.05% is the combined standard uncertainty, and the coverage factor, k = 2, is determined from the Student's t-distribution corresponding to 60 degrees of freedom.

The certified value and expanded uncertainty of the SRM 1196 cigarettes were determined to be (90.0 ± 2.1) PFLB.[50] The physical properties of the cigarettes were:

- Length: 83 mm ± 2 mm
- Tobacco packing density: 0.270 g/cm^3 ± 0.020 g/cm^3
- Mass: 1.1 g ± 0.1 g
- No filter tip
- Unbanded paper

The expiration date was set as August 31, 2020. This 10-year duration was consistent with the original choice for the SRM 1082 cigarettes.

TABLE 8 Performance data for commercial cigarettes purchased in 2007

Cigarette	Number of Determinations	PFLB
A	80	44
B	80	66
C	80	73
D	80	0

TABLE 7 Performance data for different vintages of the commercial test cigarette

	PFLB					
Vintage	Set 1	Set 2	Set 2	Set 4	Set 5	Mean and standard uncertainty or range[a]
1992	84	88	95			89 ± 5
2001	75	78	85	68	73	76 ± 6
2006	75	83				75 to 83
2007	35	35				35
2008	48	45	43	50	50	47 ± 3

[a]Standard uncertainty of each determination.

The remainder of the 10 000 cartons were stored in a chiller at −18°C (0 °F). NIST would perform periodic testing to verify that the cigarettes continued to produce the same test result.

Sales of SRM 1196 cigarettes began in September 2010.

The SRM 1196 cigarettes are now cited for use in the testing of soft furnishings in the U.S. The CPSC modified 16 CFR Part 1632 to require these cigarettes for mattress and mattress pad testing, effective September 23, 2012. For furniture mock-up testing, NFPA made a similar change in NFPA 260 and 261 in 2013. California TB 117 also required the use of SRM 1196 cigarettes or equivalent, effective in 2013. ASTM E1352 and E1353 were modified to require use of this cigarette or equivalent in 2016. The UFAC test method has not been changed to require use of SRM 1196 cigarettes as of the date of this paper.

4.3 | Research toward a standard ignition source

This effort grew out of concern that a future supply of standard, high ignition strength test cigarettes might not be established. Thus, CPSC and NIST launched a project to investigate the potential for an ignition source whose availability would transcend future changes in the materials and manufacturing sectors, such as the mandated re-design of the CTC and the manufacturing change in Whatman No. 2 filter paper.

The history of studying non-flaming (smoldering) combustion emerged as a science in the early 20th century with the modeling of self-ignition by Semenov and Frank-Kamenitskii.[51] The real-world ignition source was biological activity, and the fuels were, for example, large masses of coal, sisal rope, cotton linters, and silage.

As soft furnishings became more and more prevalent during the middle of the 20th century, concerns arose for their non-flaming ignition and subsequent smoldering. At this time, cigarette smoking had become popular, and it soon was recognized that cigarette ignition of soft furnishings was a significant fire hazard. However, ignition by a cigarette was a slow and poorly repeatable process. Thus, experimentalists developed a variety of more effective heat sources to ignite materials that were prone to smoldering.

NIST compiled these sources from an extensive review of the archival literature.[52] These included a variety of electrically powered devices, oven-heated metal pieces, and reacting materials. The report also reviewed the thermal characteristics of cigarettes, the parameters that affected whether ignition occurred, the response of substrates to the presence of a lit cigarette, and the measurement techniques used to characterize the ignition process.

In a second report,[53] NIST researched and tested SRM 1196 cigarettes and a wide range of candidate alternative ignition sources on substrates that represented the top surfaces of mattresses and the flat and crevice sites in upholstered furniture. The candidate sources included a variety of stationary hot spots, traveling hot spots, and hot rods. Some of these were electrically heated during the substrate exposure and others were pre-heated in an oven. There were also radiant heaters, materials that themselves combusted to generate the heat for testing, and ampules containing exothermically reacting chemicals.

Note that this evaluation could not have been performed without the availability of SRM 1196 cigarettes. There were very few of the vintage CTCs remaining, and the FSC version of this brand-style had the mandated low ignition strength.

Figure 9 shows the apparatus used in the testing. This research mock-up preserved the fabric/foam contact and layout of the furniture and mattress test methods, but was designed to provide additional information regarding the thermal behavior of the candidate ignition sources. More information can be found in Reference 53.

The test substrate consisted of a layer of upholstery fabric over a 50 mm thick slab of non-fire-retarded flexible polyurethane foam. The outer diameter of the acrylic frames was 203 mm. The crevice frame was hinged at 90°, but was otherwise the same as the flat frame. For each frame, attached to the frame surface and in contact with the fabric were six unsheathed Type K thermocouples, stretched parallel to the axis of the cigarette and spaced at nominally 4 mm. The testing used bead diameters of 0.075 and 0.125 mm.

Observations were made of the size of the heated area of the source and substrate relative to the coal of a cigarette, how well the substrate temperature field and the movement of that field related to those of a cigarette, and any distortion of the substrate by the ignition source. There was also assessment of the practicality of these sources in a test method that would be used for routine rating of fabrics and padding materials.

An ideal cigarette surrogate (or standard ignition source, SIS) in a test method needs to have mass and dimensions similar to a commercial cigarette (for similar substrate contact) and a hot zone that is similar in size and temperature to a cigarette coal. If the hot zone of the surrogate does not move in a manner similar to that of a cigarette coal, experimentation would be needed to determine the effect of a faster or slower speed on substrate ignition probability.

In addition, for the SIS to be a "safety-neutral" replacement for the SRM 1196 cigarette (as the modern replacement for the CTC), testing using the SIS should categorize furnishing materials and composites in the manner that they are categorized when tested with SRM 1196. Arriving at a truly equivalent ignition source requires careful replication of the properties of SRM 1196 and/or enhanced knowledge of the physics of the ignition process.

SRM 1196 cigarettes were tested on 54 fabric/foam combinations to identify suitable substrates on which to determine the similarity of alternate ignition sources to the cigarette.

NIST was unable to identify a candidate that matched the ignition probability of the SRM 1196 cigarette and behaved in a similar manner on the test substrates, despite extensive variation of the source thermal and physical properties. For the candidate sources that were electrically heated during a determination, the electrical power wiring disrupted the test materials (eg, the cover sheeting) and/or greatly slowed the rate at which replicate tests could be performed. The high mass of many of the candidate sources led to the source descending into the degraded fabric/foam substrate, changing the thermal physics from that of the much lighter cigarette. The temperatures of the

FIGURE 9 Photographs of flat (left) and crevice (right) substrates with fine thermocouples to characterize surface temperature distribution and spread rate

stationary hot spot sources needed to match the ignition probability of the SRM 1196 cigarette were much higher than the peak cigarette temperature. For the moving hot spot sources, it was not possible to obtain a combination of the movement speed and steadiness and the peak temperature that were measured in the ignition tests with SRM 1196 cigarettes.

The most promising concept for further examination was a cylindrical rod or cylinder, preheated in an oven. However, identifying an acceptable replicate of the SRM 1196 cigarette would require extensive testing in which the materials, dimensions, shape, and mass were all systematically varied. Further testing would be needed to identify a set of fabrics which, when supported on a foam slab, would lead to some, but not 100% ignitions in order to demonstrate equivalence to the SRM 1196 cigarette. Because of the high amount of this research and the low likelihood of success, NIST continued to focus on obtaining another supply of SRM 1196 cigarettes.

TABLE 9 NIST ignition strength test results in 2019 for verifying the ignition strength of SRM 1196 cigarettes Using the steel/paper substrate in ASTM E2187-16

Determinations	# of FLB	PFLB
40	36	90.0
40	38	95.0
40	37	92.5
40	38	95.0
40	37	92.5
40	38	95.0
40	38	95.0
40	39	97.5
40	37	92.5
40	39	97.5
40	37	92.5
40	39	97.5
40	37	92.5
40	37	92.5

4.4 | SRM 1196a

By 2016, the sales rate of SRM 1196 cigarettes was approaching 1600 cartons per year, exceeding expectations. At this rate, the supply would be depleted before the expiration date. This led NIST to begin the process of procuring a second supply of cigarettes.

Multiple efforts to secure a manufacturer ran into unanticipated failure. Among the reasons was that domestic manufacturers had fully converted to the design and production of FSC cigarettes. Furthermore, non-filter cigarettes had become a niche market, and the conversion of manufacturing machines to these cigarettes (and back) would remove the machines from their principal functions for a disproportionate time. This failure led to temporary perturbation of the testing of upholstered furniture and mattresses. The impact of this disruption on overall fire safety is currently unknown, but might be estimated from future analysis of fire incidence data.

In view of these commercial constraints, NIST conducted research to determine whether the ignition strength of a 100 mm filter tip cigarette, conventional except for being made with non-banded paper, would approach that of the SRM 1196 cigarette. NIST was able to obtain some such cigarettes whose tobacco column length was the typical 70 mm long. The ignition strength was measured as approximately 90 PFLB when tested on the brass plate substrate with a single sheet of filter paper. This was within the range in the original specification for the SRM 1196 cigarettes. The result also supported the concept that it was indeed the bands that largely accounted for the reduction in cigarette ignition strength.

With this option in hand, in 2019 NIST again solicited proposals for SRM 1196a cigarettes of either a non-filter design similar to SRM 1196 or a design similar to contemporary filter tip cigarettes. The key criterion was an ignition strength equivalent to that of SRM 1196 cigarettes.

The solicitation was successful, and NIST selected Flatwater Solutions Company and its subsidiary, Ho-Chunk, which is owned by the Winnebago Tribe of Nebraska. The company proposed a non-filter tip design. NIST measured the ignition strength of prototypes of this design, determined that they did have the requisite ignition strength, and placed an order for 30 000 cartons (6 million cigarettes).

Prior to the arrival of the new cigarettes, a single operator performed 14 tests (560 determinations) of SRM 1196 cigarettes. The results, shown in Table 9, show a total of 527 full-length burns. In all, the mean value was 94.1 PFLB and the corresponding 95% confidence interval, based on a binomial distribution, was 91.8 to 95.9 PFLB. This is consistent with the certified value of the SRM 1196 cigarettes from 2010, suggesting that the ignition strength of the cigarettes had not changed substantially since then.

Upon the arrival of the SRM 1196a cigarettes, NIST selected 20 cartons at random for certification testing. Seven operators performed their tests in half-day blocks. The cigarettes were selected from the 20 cartons in random order. Operators 1 and 2 performed tests every day during the certification and Operators 3 through 7 each performed half their determinations on one day and the remaining half on a second day. The results are compiled in Table 10.

TABLE 10 NIST ignition strength test results for use in establishing the ignition strength of SRM 1196a cigarettes using the steel/paper substrate in ASTM E2187-16

Test Operator	Determinations	# of FLB	PFLB
1	380	365	96.1
2	180	174	96.6
3	48	44	91.2
4	48	46	95.8
5	56	54	96.4
6	44	43	97.7
7	44	43	97.7
Total	800	767	95.6

A Bayesian statistical analysis[29] was used to establish the ignition strength value and its expanded uncertainty, *U*, from full length burn tests conducted by seven operators at NIST.

The resulting ignition strength and standard uncertainty for SRM 1196a cigarettes were certified to be (95.6 ± 2.0) PFLB.[54] The expanded uncertainty is at the 95% probability level. Although the expanded uncertainty of the certified value was not computed using the methods in the ISO/JCGM Guide,[49] the results of the Bayesian analysis can be interpreted in essentially the same way as the results from the ISO approach. The expanded uncertainty was expressed as $U = ku_c$, where u_c = 1% is the combined standard uncertainty, and the coverage factor, k = 2, was based on a normal distribution.

This was comparable to the performance of the original SRM 1196 cigarettes, whose certified ignition strength and standard uncertainty were (90.0 ± 2.1) PFLB.

The physical properties of the SRM 1196a cigarettes were:

- Length: 83 mm± 2 mm
- Tobacco packing density: 0.270 g/cm^3 ± 0.020 g/cm^3
- Mass: 1.1 g ± 0.1 g
- No filter tip
- Unbanded paper

The duration of the certification was set at February 1, 2025. Every 5 years, NIST will conduct stability testing to ensure that ignition strength of the SRM 1196a remains unchanged. NIST will also retain cartons of the SRM 1196 cigarettes and test samples from these periodically in order to establish the longevity of this type of cigarette.

FIGURE 10 Photograph of packs of SRM 1082, SRM 1196, and SRM 1196a

The SRM 1196a cigarettes were available for sale in February 2020. From that point, only SRM 1196a cigarettes were available for purchase.

5 | CONCLUSION

As early as 1980, cigarette ignition of soft furnishings (beds and residential upholstered furniture) has been recognized as the most common initiating event in fatal fires in the U.S. These losses have declined over the past four decades. Significant factors in this decline were the regulation of (a) CIR of soft furnishings and their components and (b) the reduced ignition propensity of cigarettes.

There have been five essential components in achieving and sustaining this improved fire safety. Failure of any one of these would have compromised this accomplishment.

1. Test methods that accurately reflect the physics of the ignition process,
2. Regulations citing the test methods and establishing substantive performance criteria,
3. Means for assuring the reliability and reproducibility of the test data,
4. Responsiveness of manufacturers in evolving their products, and
5. Adaptation to exogenous changes that might have compromised the first four components.

The two cigarette Standard Reference Materials, SRM 1082 and SRM 1196, have been at the heart of Components 3 and 5.

The establishment of SRM 1082:

- Provided a large, uniform, and durable supply of cigarettes with a performance in ASTM E2187 that was in the range of the pass/fail criterion in the FSC regulations;
- Assured manufacturers and regulators of cigarette brand style compliance with the FSC regulations;
- Enabled quality control of the fire test performance of the manufactured cigarettes;
- Enabled assurance of uniform test results in different labs;
- Obviated the effects on fire safety of changes in cigarette ignition performance as tobacco crops and smokers' habits and preferences changed over time; and
- Enabled development and standardization of a new ASTM E2187 test substrate, equivalent in performance to the mandated test substrate, when the original substrate material was no longer available.

The establishment of SRM 1196:

- Provided a large, uniform, and durable supply of cigarettes for assurance of consistent evaluation over time of the ignition resistance of mattresses, mattress pads, upholstered furniture, and furniture components using the CPSC, California, ASTM, and NFPA test methods;
- Enabled assurance of uniform test results in different labs;
- Obviated possible periodic and unknown changes in the CIR of soft furnishings as changes in tobacco crops and smoker preferences led to evolving ignition strength of the original commercial test cigarette over time; and
- Provided a cigarette to test soft furnishings that was stronger than most cigarettes being smoked after manufacture of the original commercial test cigarette ceased.

Each cigarette will serve as an archival reference ignition source for addressing any future changes that affect the test method(s) in which it is used.

Figure 10 shows packs of the SRM 1082 cigarettes and the SRM 1196 and SRM 1196a cigarettes.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article

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ENDNOTES

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

[ii] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

[iii] Copies of all reports generated under these two Acts may be downloaded for free from https://www.nist.gov/el/fire-research-division-73300/less-fire-prone-cigarettes or obtained from the Consumer Product Safety Commission, Bethesda, MD at www.cpsc.gov.

[iv] A physical specification of the reduced ignition propensity cigarettes would not have been sufficient. The “regular” Merit cigarettes and the test market Merit cigarettes had the same dimensions and mass.

[v] These included clarifying when personal protective gear must be available; unit conversions; the location and the device for marking the cigarettes; indicating that the unperturbed smoke column height can be estimated; and allow a laboratory how to address the intent of the non-contamination requirement.

[vi] There are potential fire safety implications for the SRM 1082 test value obtained using a substrate of China Whatman No. 2 being far lower than that obtained using U.K. Whatman No. 2 paper, even though the ignition strength of the SRM 1082 cigarettes had not changed. Commercial cigarette designs tested with the China paper will also give test

results lower than those with the U.K. paper. Thus, commercial cigarettes might meet the regulatory requirement of no more than 25 PFLB with the China paper, whereas they might have been "over the line" had they been tested using the U.K. paper. Alternately worded, cigarette ignition strengths might well have migrated upward since 2011. The effect of this weakening of the test method might offset some of the gain in fire safety resulting from the mandating of FSC cigarettes. No analysis of this hypothesis has yet been reported.

[vii] The PFLB values for the SRM 1082 cigarettes might seem slightly higher than the certified value, although the results are well within the uncertainties. In fact, they might actually be marginally higher. Whatman No.2 filter paper (U.K.) had been known to have a rougher side and a smoother side. Multiple laboratories had found that the testing with the rough side up in the 2004 version of ASTM E2187 produced PFLB values that were approximately 5% higher than the values obtained with the smooth side facing upward. Testing using ASTM E2187-04 did not specify the paper orientation, and it was presumed that the orientation in tests was random. Since 2009, the standard has required that the filter paper be oriented with the rough side facing upward if a difference could be felt.

[viii] In the following text, "confidence interval" refers to the uncertainty around an individual reported PFLB based on the number of determinations that went into that result. "Consensus interval" refers to the uncertainty in the consensus estimate (ie, the estimate arrived at after combining all of the individual PFLBs) based on the spread of the individual PFLB values, the uncertainties of each PFLB, and the number of PFLBs considered.

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