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# The Effect of Cigarette Characteristics on The Ignition of Soft Furnishings

Technical Study Group
Cigarette Safety Act of 1984

October 1987

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# Mission and Members

The Technical Study Group on Cigarette and Little Cigar Fire Safety was established by Public Law 98-567, the Cigarette Safety Act of 1984, on October 30, 1984. Its mission is to:

*"undertake such studies and other activities as it considers necessary and appropriate to determine the technical and commercial feasibility, economic impact, and other consequences of developing cigarettes and little cigars that will have a minimum propensity to ignite upholstered furniture or mattresses. Such activities include identification of the different physical characteristics of cigarettes and little cigars which have an impact on the ignition of upholstered furniture and mattresses, an analysis of the feasibility of altering any pertinent characteristics to reduce ignition propensity, and an analysis of the possible costs and benefits, both to the industry and the public, associated with any such product modification."*

Copies of this or any other reports of the Technical Study Group may be obtained from Mr. Colin B. Church, Secretariat, Technical Study Group, Consumer Product Safety Commission, 5401 Westbard Avenue, Washington, D.C., 20207.

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## Introduction

Cigarette ignition of furniture is by far the leading cause of fire deaths and injuries in the United States. While more ignition-resistant furnishings are being manufactured, fire casualties could be more rapidly reduced if cigarettes were manufactured to cause fewer ignitions. To provide both the fundamental understanding of the cigarette/furniture ignition process and practical application of that knowledge, the Center for Fire Research of the National Bureau of Standards pursued the following fundamental and applied research tasks under the Cigarette Safety Act of 1984.

- Identify the characteristics of cigarettes that could lead to a reduction in ignition propensity (using experimental cigarettes of well-characterized composition and construction supplied by the cigarette industry);
- Obtain and analyze data to verify the composition of and statistical variation in the experimental cigarettes in order to provide a reliability analysis of laboratory findings using those cigarettes;
- Measure the ignition propensities of patented, non-commercial cigarettes, as supplied by their inventors;
- Validate the cigarette ignition propensity data from the bench-scale testing by comparison with test results, using real furniture items (supplied by the furniture industry) indicative of the most common or high risk types;
- Elucidate the thermal conditions associated with lit cigarettes, their energy transfer to various substrates, and the ensuing ignition process;
- Create a computer model of the ignition process to enable prediction of the direction and approximate magnitude of effects of variations in the characteristics of a cigarette on its ignition propensity;
- Quantify the effect of smolder-promoting alkali metal ion concentration in fabrics and paddings on their susceptibility to smoldering ignition by cigarettes to account for the effect of ignitability variations within or between lots of commercially-produced upholstery materials; and
- Develop a laboratory method for measuring the ignition propensity of cigarettes.

## Approach

This research project comprised several concurrent, interactive studies. These ranged from computational to experimental, fundamental to empirical.

### 1. Materials

A common set of materials was used in the various laboratory experiments. Forty-one types of experimental cigarettes were specially prepared for this study by the cigarette industry. They varied in tobacco type and density, paper permeability and citrate content, and circumference. The wrappers and fillers were selected for systematic and broad property variation, not necessarily indicative of current commercial cigarettes. Laboratories expert in the appropriate measurements were commissioned to characterize the composition of and variance in these cigarettes. Five embodiments of cigarette patents were received from their inventors. Several commercial cigarettes, remaining from a prior project under the Act, were used here as well. Selected fabrics and padding materials were acquired in large quantities to allow for the numerous bench-scale and full-scale tests.

### 2. Performance Measurements

Ignition performance measurements of the cigarettes were carried out on substrates having a range of ignition resistance, including some which simulated the most easily-ignited furniture. At least five replicate tests were performed for each cigarette/substrate combination. The data were statistically analyzed for correlations between numbers of ignitions and the individual cigarette characteristics. Similar testing was performed on chairs manufactured of some of the same materials, and the data analyzed to determine the extent to which the results were predicted by the small-scale tests.

### 3. Thermophysics of the Ignition Process

The ignition process was assumed to depend on the energy transfer from cigarettes to furniture items. This was studied using fine thermocouples and a heat flux gauge to follow the temperature and energy flux histories while cigarettes smoldered on different substrates. Two- dimensional infrared imaging radiometry was used to map the thermal response of the substrate. Graphical correlations were explored between measured properties of the burning cigarettes and the measured ignition propensities.

### 4. Modeling Ignition

Both fundamental and semi-empirical mathematical modeling of the lit cigarette and ignition of the substrate were pursued. Each borrowed heavily from prior efforts elsewhere. A comprehensive list of the involved materials properties and physical processes was compiled. Substantial simplifications were made in representing these. The predictions from the resulting FORTRAN programs were tested, to a limited extent, against the trends observed in the laboratory tests.

### 5. Effects of Materials Treatment

Fabrics were treated with known concentrations of alkali metal chlorides and tested for changes in cigarette ignition resistance. Similar comparative tests were performed on clean fabrics, to which was added soil extracted from used fabrics.

### 6. Test Method Development

Finally, the experience and knowledge gained from the above research were applied to the task of developing a convenient, accurate test method for cigarette ignition propensity. Several previously-suggested and new approaches were analyzed and tested in the laboratory, but the development of a viable test method has not yet been completed.

## Table ES-1. Ignition Propensities of Selected Test Cigarettes

| | Designation | No. Ignitions 20 Tests | % |
|---|---|---|---|
| Experimental Cigarettes | | | |
| | 201 | 0 | 0 |
| | 106 | 1 | 5 |
| | 202 | 2 | 10 |
| | 130 | 4 | 20 |
| | 114 | 4 | 20 |
| | 105 | 6 | 30 |
| | 113 | 6 | 30 |
| | 108 | 7 | 35 |
| | 122 | 7 | 35 |
| | 129 | 10 | 50 |
| Least Ignition-Prone Commercial Cigarettes | | | |
| | 1 | 16 | 80 |
| | 2 | 12 | 60 |
| Typical Ignition Propensity Commercial Cigarettes | | | |
| | 3 | 18 | 90 |
| | 6 | 20 | 100 |

## Table ES-2. Ignition Propensity as a Function of Experimental Cigarette Characteristics

| Cigarette Parameters | Number of Ignitions/Tests | % |
|---|---|---|
| Tobacco Packing Density | | |
| High | 282/320 | 88 |
| Low | 153/320 | 48 |
| Cigarette Circumference (mm) | | |
| 25 | 243/320 | 76 |
| 21 | 192/320 | 60 |
| Paper Permeability | | |
| High | 256/320 | 80 |
| Low | 179/320 | 56 |
| Paper Citrate Conc. (%) | | |
| 0.8 | 231/320 | 72 |
| 0 | 204/320 | 64 |
| Paper Citrate (%) (Low Ignition Propensity Cigarettes) | | |
| 0.8 | 47/100 | 47 |
| 0.0 | 23/100 | 23 |
| Tobacco Type | | |
| Flue-cured | 222/320 | 69 |
| Burley | 213/320 | 66 |

## Conclusions

Substantial progress has been made in understanding how to study cigarette ignition, the nature of the cigarette ignition process, and the effects of cigarette characteristics on both the thermal physics and the observed ignition of furniture.

The principal findings of this research are as follows.

- In furniture mock-up tests involving a wide range of fabrics and paddings, the best of the experimental cigarettes tested had considerably lower ignition propensities than commercial cigarettes.
- Three cigarette characteristics were found to reduce ignition propensity significantly: low tobacco density, reduced circumference, and low paper permeability. Considerably larger reductions were achieved with combinations of these. The tobacco column length, the presence of a filter tip, and citrate content of the paper had effects in limited cases. The tobacco blend had minimal impact on ignition propensity.
- Non-ignitions were often achieved without the cigarettes self-extinguishing during the test; i.e., many cigarettes burned their full length without igniting the substrate.
- Some of the best-performing experimental cigarettes had average per puff tar, nicotine, and CO yields comparable to or only slightly greater than typical commercial cigarettes.
- Each of five patented cigarette modifications also showed reduced ignition propensity over cigarettes that were identical except for the patented feature. These included variations in the paper, an additive to one location of the tobacco column, an additive throughout the tobacco column, and an additive to the exterior of the paper.
- Ignition results from the bench-scale testing correlated very well with corresponding data from experiments with chairs made with the same fabrics and padding materials.
- The physics of the ignition process is a function of both the cigarette and the substrate. Therefore, an accurate ignition propensity measurement apparatus must involve the two components.
- Intrusive probes of the ignition process (e.g., thermocouples, heat flux gauges) perturb the delicately balanced system. The induced errors can be estimated if the probes are small and well-selected. With care, (non-intrusive) infrared imaging can be used to study the thermal profiles on non-igniting or igniting substrates.
- An approximate correlation exists between the cigarette coal area and ignition propensity. Peak coal surface temperatures (and thus peak heat fluxes) did not vary sufficiently to demonstrate a correlation with ignition tendency for the cigarettes tested.
- Oxygen depletion in the vicinity of the ignition site is important during the ignition process, but is sufficiently similar for all cigarettes examined so as not to account for their relative ignition propensities.
- It is possible to construct a complex computer model of the smoldering combustion of a cigarette and the response of an idealized substrate. With all its simplifications, this preliminary model is sufficiently realistic to (1) manifest the most important and most sensitive physical features of the ignition process and (2) reproduce some of the cigarette characteristics that do and do not affect ignition propensity. Thus, the model could potentially be used to screen possible combinations of (included) charac-

### Table ES-3. Average Per Puff Smoke Component Yields from Selected Cigarettes

| Experimental Cigarettes | Tar (mg) | Nicotine (mg) | CO (mg) |
|---|---|---|---|
| 105 | 1.6 | 0.09 | 1.9 |
| 106 | 1.8 | 0.10 | 2.0 |
| 108 | 1.3 | 0.09 | 1.1 |
| 113 | 2.4 | 0.19 | 2.2 |
| 114 | 2.6 | 0.21 | 2.1 |
| 122 | 2.4 | 0.15 | 2.4 |
| 130 | 2.5 | 0.20 | 2.2 |
| 201 | 2.5 | 0.18 | 2.5 |
| 202 | 2.0 | 0.16 | 2.4 |
| Average for 6 Most Popular Commercial Cigarettes | 2.0 | 0.13 | 1.7 |

Possible differences in the composition or toxicology of the smoke delivered by these cigarettes have not been investigated.

### Table ES-4. Ignition Propensities of Patented Cigarettes

| Designation | No. Ignitions / No. Tests | Percent |
|---|---|---|
| 301-Control | 25/25 | 100 |
| 301 | 29/50 | 58 |
| 302-Control | 24/25 | 96 |
| 302 | 10/50 | 20 |
| 303-Control | 24/25 | 100 |
| 303 | 32/60 | 53 |
| 304-Control | 25/25 | 100 |
| 304 | 33/50 | 66 |
| 305-Control | 25/25 | 100 |
| 305 | 13/60 | 22 |

**Table ES-5. Comparison of Ignition Propensities of Tested Cigarettes at Full- and Reduced-Scales**

| Cigarette Number | Percent Ignitions: Bench-Scale | Percent Ignitions: Full-Scale |
|---|---|---|
| 6 | 74 | 73 |
| 129 | 13 | 23 |
| 106 | 3 | 6 |
| 114 | 6 | 14 |
| 201 | 0 | 6 |

teristics that offer increased fire safety. At present, however, the code for this preliminary model is very slow and not user-friendly.

- The current, mini-mockup methods are valid for *research* measurements of the ignition propensity of cigarettes. However, their use in a *standard* test method of cigarette performance is compromised by the variability in the commercial fabrics and paddings used in the mockup.
- Several alternative candidate test methods for measuring the cigarette ignition propensity of soft furnishings were evaluated; none was usable in its current state of development. Two promising approaches to cigarette testing are proposed. The first modifies the existing mockup procedure using specially-prepared, well-controlled fabrics and paddings. The second uses a non-reactive substrate at variable temperature to determine the minimum needed cigarette heat-loss rate for extinguishment. All need further development before promulgation.

## Priority Further Research Directions

In any closed-end research effort such as this one, there are many ideas that cannot be pursued and others that evolve during the project. The following is a tabulation of those studies whose results are important to a sound understanding of the cigarette/furniture ignition phenomenon and to realization of the research into practical usage.

- Both cigarette manufacturers and the public need a test to determine how less ignition-prone cigarettes perform. The test should be relatable to the real-world situation and should be simple enough to be used as part of a quality assurance program. Three promising approaches for distinguishing between high, moderate, and low ignition propensity cigarettes are:
  - Testing with non-smoldering (inert) substrates, e.g., extinguishment of cigarettes on a glass plate or a porous frit, heated to adjusted, controlled temperatures.
  - Testing with alternative reactive (smoldering) substrates, such as with controlled addition of selected amounts of smolder-enhancing ions to multiple layers of α-cellulose paper.
  - Testing with controlled reactive fabric/padding substrates; mockup testing using "standardized" substrates created by the addition of selected amounts of smolder-enhancing ions.
- The current research has indicated positive directions for reducing cigarette ignition propensity. Research is needed on more combinations of these factors, especially lower tobacco content and modified paper permeability and thickness. Variations selected with the computer model should also be studied.
- Performance data for current market cigarettes should be generated by use of a new test method. These data could then be compared to future year cigarette performance.
- For a wider range of cigarettes and substrates, extensive research is needed to better measure and define the effect of the substrate on cigarette ignition propensity, the ignition kinetics, and the components of heat transfer (radiation, convection, conduction).
- More measurements are needed of the cigarette ignition physics in crevice configurations.
- The preliminary computer model of the smoldering cigarette, while operational, would benefit from key upgrades: multi-step tobacco pyrolysis and combustion, including changes resulting from paper modification; inclusion of free and combustion-generated water; more realistic movement of air and combustion gases within the cigarette; and detailed paper behavior (changes in permeability and combustibility) as a function of temperature.
- Similarly, the substrate model should be amended to include: two-layer (fabric plus padding) construction, heat-induced reactivity, and crevice geometry capability.
- The computer models should be made more time-efficient for efficient parametric variation of cigarette and substrate variables.

The Effect of
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# Section 1

## Introduction

## Contents for Section 1

# I Introduction

## Project Background

Cigarette ignition[1] of furniture is by far the leading cause of fire deaths and injuries in the United States [1-1]. Although the actual probability of a dropped, lit cigarette igniting soft furnishings and leading to a death or injury is small (49,000 fires [1-1] from 600 billion cigarettes purchased [1-2] in 1984), there were a sufficient number of such occurrences that an estimated 1530 deaths and 3950 injuries occurred [1-1]. These most often happen in residences when a lit cigarette is dropped onto bedding or a piece of upholstered furniture. The fabric and/or padding smolder slowly and for a long time, and then often burst into flames. The victims succumb to burns and/or to inhaled toxic smoke.

For over a decade, intense efforts have been devoted to reducing the susceptibility to cigarette ignition of both upholstered furniture and mattresses (soft furnishings). The implementation of a mandatory standard for mattresses [1-3] and voluntary standards for upholstered furniture [1-4,5] has resulted in the manufacture of soft furnishings with improved resistance to cigarette ignition. The newer furnishings show a reduction in total fire losses, but an increase in the risk of death or injury per fire [1-6]. Moreover, these commodities have average useful lifetimes of fifteen to twenty years [1-7]. Thus, the full impact of the improved furnishings on fire safety will not be realized for decades to come. By contrast, cigarettes are consumed with a few months of their production [1-8], leading to the possibility that fire deaths and injuries could be reduced more rapidly if the cigarette were also suitably modified.

In response to this, Public Law 98-567, the "Cigarette Safety Act of 1984," was passed by the 98th Congress and signed into law on October 30, 1984. It established an Interagency Committee to direct, oversee, and review the work of a Technical Study Group on Cigarette and Little Cigar Fire Safety (TSG). The TSG was directed to:

*"undertake such studies and other activities as it considers necessary and appropriate to determine the technical and commercial feasibility, economic impact, and other consequences of developing cigarettes and little cigars that will have a minimum propensity to ignite upholstered furniture or mattresses. Such activities include identification of the different physical characteristics of cigarettes and little cigars which have an impact on the ignition of upholstered furniture and mattresses, an analysis of the feasibility of altering any pertinent characteristics to reduce ignition propensity, and an analysis of the possible costs and benefits, both to the industry and the public, associated with any such product modification."*

The TSG constructed its initial work plan in February, 1985 and refined it through October, 1986. As part of this plan, the Center for Fire Research (CFR) of the National Bureau of Standards (NBS) was sponsored to perform the following research:

### Commercial Cigarette Testing

Determine the extent to which commercially available cigarette packings[2] vary in their propensity to ignite soft furnishings substrates.[3]

### Ignitability Measurement

- Review and summarize the prior state-of-the-art in understanding cigarette ignition of soft furnishings;
- Identify the characteristics of cigarettes that could lead to a reduction in ignition propensity;
- Measure the ignition propensities of selected patented, non-commercial cigarettes, as supplied by their inventors;
- Elucidate the thermal conditions associated with lit

[1] *Ignition is defined as sustained, expanding smoldering of the material on which the burning cigarette rests. This may or may not lead to flaming ignition.*

[2] *A cigarette packing is defined as a commercial cigarette, described by its name, its diameter, its length, whether menthol or non-menthol, whether filter or non-filter, and by its package type (e.g., soft pack).*

[3] *The term "substrate" is used to describe one combination of a specific fabric and padding, in either the flat or the crevice (juncture of vertical and horizontal cushions) configuration, with or without a sheet covering the cigarette. An example is the flat area of a piece of polyurethane foam covered with a specific fabric, with the cigarette covered by a piece of sheeting. The crevice made from the same materials is a different substrate.*

cigarettes, their energy transfer to various substrates, and the ensuing ignition process (using experimental cigarettes of controlled and well-characterized composition and construction supplied by the cigarette industry);
- Create a computer model of the ignition process to enable prediction of the direction and approximate magnitude of effects of variations in a cigarette's characteristics on its ignition propensity; and
- Develop a laboratory method for measuring the ignition propensity of cigarettes.

#### Quality Assurance of Experimental Cigarettes

Obtain and analyze data to verify the composition of and statistical variation in the experimental cigarettes obtained from the cigarette industry in order to provide a reliability analysis of laboratory findings using those cigarettes.

#### Alkali Metal Ion Effects

Quantify the effect of alkali metal ion concentration in fabrics and paddings on their susceptibility to smoldering ignition by cigarettes. Since alkali metal ions are known smolder promoters, this is pivotal to reducing or accounting for the effect of ignitability variations within or between samples of commercially-produced upholstery materials. A similar exploratory study was to be performed on the effect of in-use soiling on smoldering ignition.

#### Full-Scale Furniture Testing

Validate the cigarette ignition data from the bench-scale testing by comparison with test results using real furniture items. This project used selected furniture items, supplied by the furniture industry and made of fabrics and paddings covering a wide range of ease of cigarette ignition (Some represented pre-UFAC and BIFMA standards of construction.) This allowed a more accurate assessment of the impact of the changes in cigarettes and more realistic input for the benefit/cost model.

Separate reports have already been issued on two of the topics: "Relative Propensity of Selected Commercial Cigarettes to Ignite Soft Furnishings Mockups," by John F. Krasny and Richard G. Gann, [1-9] and "Cigarette Ignition of Soft Furnishings - A Literature Review With Commentary," by John F. Krasny [1-10]. The present report is a unified presentation of the approach, procedures, results and conclusions from the remainder of the CFR study.

## Nature of This Project

The work reported here ranges from basic research into the physics of the ignition process to highly empirical studies of the manifest cigarette features affecting ignition.

Substantial progress has been made in understanding how to study cigarette ignitions, the very nature of that process, and the effects of cigarette construction on both the thermal physics and the observed ignition of soft furnishings. Nonetheless, the research is incomplete. It was not possible, nor was it the intent, to resolve fully all the technical issues involved in cigarette-initiated fires. The authors have therefore been attentive to documenting the experimental rationale, the procedures developed, and the logic utilized in interpreting the results. These will enable future researchers to evaluate this work and use the appropriate portions to further advance the field.

The report begins with a description of the materials used in the various parts of the project. It then proceeds to the cigarette performance experiments, both at bench and full scales. Next is a presentation of the research into the physics that controls the ignition process, followed by an accounting of the transfer of that knowledge into a computer model. The report continues with the rationale for and initial efforts to develop a new test method for measuring cigarette ignition propensity. Last are conclusions and a listing of unresolved issues worthy of further research.

# References for Section 1


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[1-3] "Standard for the Flammability of Mattresses and Mattress Pads," 16 Code of Federal Regulations, Part 1632, 1973.

[1-4] "Cigarette Ignition Resistance of Components of Upholstered Furniture," NFPA 260A-1983, National Fire Codes, National Fire Protection Association, Quincy, MA, published annually.

[1-5] "Resistance of Mock-up Upholstered Furniture Material Assemblies to Ignition by Smoldering Cigarettes," NFPA 260B-1983, National Fire Codes, National Fire Protection Association, Quincy, MA, published annually.

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[1-8] Spears, A., Lorillard, private communication.

[1-9] Krasny, J.F. and Gann, R.G., "Relative Propensity of Selected Commercial Cigarettes to Ignite Soft Furnishings Mockups," NBSIR 86-3421, U.S. National Bureau of Standards, Gaithersburg, MD, 1986.

[1-10] Krasny, J.F., "Cigarette Ignition of Soft Furnishings—A Literature Review With Commentary," NBSIR 87-3509, U.S. National Bureau of Standards, Gaithersburg, MD, 1987.

# Section 2

## Materials

## Contents for Section 2



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# Cigarettes

In this study, forty-one experimental cigarettes, five patented cigarettes, and three previously tested commercial cigarettes were used. The following is a documentation of their composition.

## Description of Cigarettes

### Series 1 Experimental Cigarettes

Thirty-two cigarettes varying systematically in five parameters at two levels were manufactured by the cigarette industry with current hardware at slower speeds. The parameters studied were 1) tobacco blend (Burley[1] or flue-cured[2]), (2) expansion[3] (non-expanded, 60 cuts/inch or expanded, 30 cuts/inch), (3) cigarette circumference (nominally 21 or 25 mm), (4) cigarette paper permeability (nominally 10 or 75 CORESTA[4]), and (5) cigarette paper treatment (untreated and treated with approximately 0.8% sodium potassium citrate). Table 2-1 gives the experimental cigarette designations with respect to the five parameters; the acronym, which is a mnemonic for the cigarette construction, and an experimental number will be used interchangeably throughout this report. Additionally, Appendix 2-A gives information concerning individuals in the cigarette industry who arranged for manufacturing the cigarettes, specifics on the designations of tobacco cut, cigarette paper, tipping paper, filter rod, the Burley and flue-cured blends, and cigarette manufacturing specifications.

[1]*An air-cured tobacco grown primarily in Kentucky and Tennessee. It is light brown to reddish brown in color and has a somewhat greater filling power than flue-cured tobacco.*

[2]*Commonly called Bright or Virginia tobacco. It is lemon or orange-yellow in color and possesses a sweet aroma and slightly acidic taste. It is high in sugar content and low to average in nitrogenous materials, acids, and nicotine.*

[3]*Expansion refers to a process which increases the volume of individual tobacco shreds.*

[4]*Corresponds to $cm^3/min \cdot cm^2$ measured at 1 cbar.*

### Series 2 Experimental Cigarettes

A second series consisted of nine cigarettes varying in paper parameters. These were produced by the cigarette industry with research hardware. The expanded, flue-cured tobacco blend was the same as used in Series 1 cigarettes. The papers contained no additives. The variables were (1) single vs. double paper wrapping of the cigarettes (the inner, second wrapping was a thin tissue paper with a permeability of 7000 CORESTA), (2) paper permeability (a base paper of 4-6 CORESTA units, with certain cigarettes covered with paper electrostatically perforated to 60 CORESTA units), and (3) embossed (raised dot pattern) vs. normal texture paper. One cigarette had nominally a 21 mm circumference, the others 25 mm. Table 2-2 gives a detailed description of the cigarette variables and the experimental designations that will be used throughout this report. Appendix 2-B gives information on the manufacturing specifications.

### Patented, Low Ignition Propensity Cigarettes

A group of non-commercial, patented cigarettes were also included in this study. The cigarettes were supplied in accordance with the Federal Register notices, vol. 51, no. 115, June 16, 1986 and vol. 51, no. 148, August 1, 1986 (Appendix 2-C). The conditions for acceptance of such cigarettes for evaluation were that the person submitting:

1. "select the single embodiment of his or her patent(s) believed to be most effective for consideration,
2. submit documents which show that a patent has been issued or that the application for a patent has been filed,
3. supply information as to the specific nature of the particular modification or additive employed in the cigarette invention in *quantitative terms,*
4. provide evidence of significantly reduced propensity of the cigarette invention to ignite substrates found in mattresses and upholstered furniture,
5. provide free of charge 300 invention cigarettes and 300 control cigarettes that are identical to the invention cigarettes except for the feature that comprises the effective ignition repression, and
6. supply uniformity data (mean value plus standard deviation) for both the patented and control cigarettes with regard to the following properties: cigarette mass, ciga-

## Table 2-1. Description of Series 1 Experimental Cigarettes

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

rette length and diameter, mass burning rate [in air], and magnitude of modification."

In publishing the results, the identities of the individual patented cigarettes were to be kept confidential; each one of the inventors would be informed only of the test results on his cigarette(s).

Five patented cigarette embodiments were submitted, each in accordance with the Federal Register notices. The embodiments, which the suppliers claim make them less ignition-prone, are listed below. No verification of the invention disclosures was made by NBS.

- "The cigarette wrapper was made to a very tight natural porosity (3 cm/min [CORESTA]) and at a higher-than-normal basis weight of 32 g/m². The paper was subsequently treated with 11% potassium citrate and electrically perforated to 70 cm/min (CORESTA)." U.S. patent application no. 06/627,710.
- Introduction of a proven and safe inorganic fire retardant (0.02 ml of sodium silicate [viscosity of 60 CP, 26% $SiO_2$]) onto 5 mm in the center of the 85 mm tobacco rod. U.S. patent application no. 06/734,118.
- "Small bands of diffusionally tight paper (containing only cellulose derived from wood pulp) were attached at fixed intervals to the inside surface of otherwise conventional cigarette wrapper.[sic] The latter has a permeability of 30 cm/min (CORESTA) and contains sodium potassium citrate [sic] at a level of 0.8% (expressed as anhydrous citric acid). The dimensions of each band are 6.5 mm by 27 mm. These were spaced, two per cigarette, so that the first band is 15 mm from the lighting end and the second

## Table 2-2. Description of Series 2 Experimental Cigarettes

| Experimental Designation | Blend | Circumference (mm) | Paper (Outer) | Paper (Inner)[a] | Construction |
|---|---|---|---|---|---|
| 201 | Flue-cured Expanded | 21 | 4-6 CORESTA Units/ 23.5 mm | None | Single Wrap |
| 202 | Flue-cured Expanded | 25 | 4-6 CORESTA Units/ 27.5 mm | None | Single Wrap |
| 203 | Flue-cured Expanded | 25 | 4-6 CORESTA Unit Base Electrostatically Perforated to 60 CORESTA Units/27.5 mm | None | Single Wrap |
| 204 | Flue-cured Expanded | 25 | 4-6 CORESTA Units Embossed/27.5 mm | None | Single Wrap |
| 205 | Flue-cured Expanded | 25 | 4-6 CORESTA Units Electrostatically Perforated to 60 CORESTA Units/Embossed/ 27.5 mm | None | Single Wrap |
| 206 | Flue-cured Expanded | 25 | 4-6 CORESTA Units/ 27.5 mm | 7000 CORESTA Microporous Structure/25 mm | Double Wrap |
| 207 | Flue-cured Expanded | 25 | 4-6 CORESTA Unit Base Electrostatically Perforated to 60 CORESTA Units/27.5 mm | 7000 CORESTA Microporous Structure/25 mm | Double Wrap |
| 208 | Flue-cured Expanded | 25 | 4-6 CORESTA Units Embossed/27.5 mm | 7000 CORESTA Microporous Structure/25 mm | Double Wrap |
| 209 | Flue-cured Expanded | 25 | 4-6 CORESTA Units Electrostatically Perforated to 60 CORESTA Units/Embossed/ 27.5 mm | 7000 CORESTA Microporous Structure/25 mm | Double Wrap |

(a) Same width as cigarette circumference, i.e., no overlap; also extends under the overwrap to the filter

is 30 mm from the lighting end. Each band has a mass of approximately 2.5 mg." (U.S. patent applied for.)

- ". . .the brush application to the exterior surface of the Commercial Cigarette of a water suspension containing (8.9%) percent by weight of Non-fat Dry Milk and (0.1%) percent by weight of Mono-ammonium Phosphate. . ." U.S. Patent 4,453,553.
- Addition to the tobacco column of Expantrol V™ (a moisture stable, intumescent silicate fire retardant material) at a tobacco to additive ratio of 4:1. U.S. patent application no. 06/877,803.

The cigarettes were coded 301 through 305, in random order. The controls were correspondingly labeled with a "C."

### Commercial Cigarettes

In a prior study [2-1], 12 commercial cigarettes were studied to determine their relative ignition propensities. Four of these cigarettes (1-3 and 6) were selected to compare with the experimental and patented cigarette performance in this study: two having the lowest ignition propensity of the twelve commercial cigarettes (1 and 2) and two with a high ignition propensity typical of eight of the commercial cigarettes (3 and 6).

## Quality Assurance of Cigarettes

### Methods for the Determination of Cigarette Characteristics

The experimental cigarettes were characterized with respect to total weight, tobacco weight, filter weight, paper weight, and circumference in the following manner:

Cigarettes which had been placed in sealed containers and placed in freezers held at −15°C upon arrival at CFR were transferred to bins in a conditioned room (55 + 10% RH, 22 ± 3°C). The cigarettes were conditioned for at least 48 hours before measurements were taken. Weights were determined on an analytical balance with 0.0001 g resolution. Cigarette dimensions were determined on a ruler with 0.5 mm resolution. Four randomly-selected replicates of each of the Series 1 cigarettes and five randomly-selected replicates of each of the Series 2 and patented cigarettes were measured. First, the cigarettes were weighed. Then a scalpel was used to cut the cigarette at the wrapper and over-wrap seam to remove the filter. The wrapper was then cut lengthwise to allow removal of the tobacco. The tobacco remaining under the over-wrap paper was removed and combined with the main tobacco column. The filter with the over-wrap paper, the tobacco, and the paper were individually weighed. The paper was flattened on a dark background and the width (circumference) and length were measured to the nearest 0.5 mm. It would have been difficult to determine the dimensions more accurately because measurements would have had to be made under a microscope.

Means and standard deviations for the values were calculated. Additionally, the packing density of each cigarette was determined based on the measured values of tobacco weight, circumference, and tobacco column length. These data are presented in Tables 2-3 and 2-4 for Series 1 and Series 2, respectively.

Values of the total cigarette weights, tar, nicotine and CO yields, and puff counts were supplied by the laboratory of Lorillard, Inc., a division of Loews Theatres, Inc., Greensboro, North Carolina. Additionally, linear and mass burn rates and tar deliveries for Series 1 cigarettes and pressure drops for Series 1 and 2 cigarettes were furnished by Lorillard. These data are presented in Tables 2-5 and 2-6.

The experimental cigarettes were also analyzed for tar, nicotine, and CO deliveries and puff count by the Tobacco Research Laboratory of The Federal Trade Commission, Washington, D.C. Approximately fifty of each of the cigarettes were removed from the freezer and sealed in zip-lock bags. The cigarettes were delivered to FTC and analyzed by established methods [2-2,3]. The results are shown in Tables 2-7 and 2-8.

Determination of the experimental cigarette tobacco blend from measurements of the total alkaloids and reducing sugars using a method given in [2-4] was performed by the Department of Crop Science, North Carolina State University, Raleigh, North Carolina. The determination for the Series 1 experimental cigarettes was made from six individually-wrapped tobacco columns of each cigarette. Three tests were performed on each of the thirty-two cigarettes using approximately one-gram samples. These data are presented in Table 2-3. Since the Series 2 cigarettes were prepared from one tobacco batch, the tobacco columns from twenty each of the nine experimental cigarettes were blended and analyzed. These data appear in Table 2-4.

The permeability of the wrapping paper on the experimental cigarettes was determined by the Kimberly-Clark Corporation, Roswell, Georgia. Approximately twenty-five of each of the two series of experimental cigarettes were supplied. The method used for the determination is briefly described in Appendix 2-D and the data appear in Tables 2-3 (Series 1) and 2-4 (Series 2).

Citrate analysis of six selected Series 1 experimental cigarettes was done by the Health Sciences Laboratory, U.S. Consumer Product Safety Commission, Washington, D.C. Fifteen wrappers of each cigarette (three with no reported citrate and three with reported citrate treatment) were removed from cigarettes stored in the freezer. The wrapper seam was removed from all samples to avoid possible contamination from the adhesive. The results are shown in Table 2-3 in parentheses. The method for determining the citrate content is described in Appendix 2-E.

### Results of Measurements of Physical and Chemical Characteristics of Cigarettes

Tables 2-3 and 2-4 show the measured physical and chemical properties of the Series 1 and Series 2 experimental cigarettes. The measured values generally indicate reasonable adherence to the design specifications of these cigarettes. No measurements are presented for the physical and chemical characteristics of the patented cigarettes. The details of the experimental cigarettes are discussed below.

**Series 1 Experimental Cigarettes**

Half of the 32 cigarettes in this series had nominally 21 mm, the other 25 mm circumference. The actual measurements—performed with a millimeter scale on papers cut off the cigarettes—confirmed these values within the accuracy of the measurement. Similarly, all tobacco columns, measured from the cigarette tip to the overwrap paper, were found to be of about the same length, about 72 mm.

The determination of the Burley or flue-cured tobacco blend was based on the amounts of reducing sugars and total alkaloid content (Tables 2-3 and 2-4). The analysts's

## Table 2-3. Measured Physical and Chemical Characteristics of Series 1 Experimental Cigarettes

| Experimental Cigarette Designation | Tobacco Analysis[a] | | | | | | | | Measured Physical Cigarette Characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total alkaloid (%) | Sugar (%) | Packing density (mg/mm³) | Perm.[b] (CORESTA)[c] | Paper citrate (conc.)[d] | Circum. (mm) | Tobacco column length (mm) | Total cigarette weight (mg) | Tobacco weight (mg) | Filter weight (mg) | Paper weight (mg) |
| 101(BNLC-21) | 1.99±0.02 | 2.66±0.28 | 0.24 | 8.9± 0.5 | 0.8 | 21.0±0 | 72.5±0.5 | 831±14 | 619±15 | 174±2 | 39±0.6 |
| 102(BNLN-21) | 2.00±0.19 | 2.48±0.19 | 0.25 | 7.8± 0.5 | 0.0 | 21.0±0 | 72 ±0.5 | 840± 6 | 627± 3 | 173±4 | 42±0.9 |
| 103(BNHC-21) | 2.04±0.04 | 2.48±0.27 | 0.25 | 75 ±10 | 0.8 | 21.0±0 | 72.5±0 | 835±36 | 626±34 | 171±2 | 39±0.5 |
| 104(BNHN-21) | 2.00±0.11 | 2.52±0.22 | 0.24 | 66 ± 7 | 0.0 | 21.0±0 | 72.5±5 | 829±14 | 618±13 | 172±2 | 41±1.1 |
| 105(BELC-21) | 1.82±0.07 | 2.07±0.34 | 0.16 | 9.4± 0.7 | 0.8 | 21.0±0 | 72 ±0.5 | 606±13 | 401±12 | 169±2 | 38±0.6 |
| 106(BELN-21) | 1.83±0.06 | 2.02±0.24 | 0.17 | 8.2± 0.5 | (0.0) | 21.0±0 | 73 ±0 | 640± 9 | 428± 7 | 172±4 | 41±0.5 |
| 107(BEHC-21) | 1.85±0.05 | 2.16±0.18 | 0.17 | 70 ±10 | (0.74) | 20.0±0 | 72 ±0.5 | 599±16 | 387±17 | 170±4 | 40±1.0 |
| 108(BEHN-21) | 1.85±0.06 | 1.89±0.23 | 0.14 | 69 ±10 | 0.0 | 21.0±0 | 72.5±0.5 | 565±40 | 356±39 | 171±2.5 | 39±0.9 |
| 109(FNLC-21) | 1.95±0.05 | 12.69±0.88 | 0.31 | 8.9± 0.6 | 0.8 | 21.0±0.5 | 73 ±0 | 985±25 | 768±25 | 174±2 | 44±0.6 |
| 110(FNLN-21) | 1.96±0.06 | 12.72±0.56 | 0.31 | 8.5± 0.6 | 0.0 | 21.0±0 | 72.5±0 | 994±17 | 777±22 | 174±5 | 43±0.4 |
| 111(FNHC-21) | 1.90±0.04 | 12.37±0.72 | 0.32 | 67 ± 7 | 0.8 | 21.0±0 | 72.5±0 | 1018±10 | 802± 6 | 176±4 | 42±0.3 |
| 112(FNHN-21) | 1.94±0.06 | 12.78±0.97 | 0.31 | 67 ± 6 | 0.0 | 21.0±0.5 | 72.5±0.5 | 992± 7 | 778± 6 | 173±2 | 41±0.7 |
| 113(FELC-21) | 1.74±0.03 | 10.37±0.69 | 0.15 | 9.2±0.6 | 0.8 | 20.5±0 | 72.5±0.0 | 588±18 | 372±16 | 175±3 | 42±1.4 |
| 114(FELN-21) | 1.69±0.06 | 10.49±0.72 | 0.15 | 8.6±0.7 | 0.0 | 21.0±0 | 72.5±0.5 | 601±17 | 385±16 | 176±1 | 42±0.7 |
| 115(FEHC-21) | 1.71±0.06 | 10.13±0.55 | 0.17 | 68 ± 5 | (0.57) | 20.0±0 | 72.5±0.5 | 607±10 | 387±10 | 174±5 | 43±0.8 |
| 116(FEHN-21) | 1.66±0.05 | 10.35±0.70 | 0.15 | 68 ± 6 | 0.0 | 21.0±0 | 73 ±0.5 | 592±14 | 376± 5 | 176±5 | 41±0.6 |
| 117(BNLC-25) | 2.01±0.13 | 2.52±0.14 | 0.24 | 9.4± 0.8 | 0.8 | 25.0±0 | 72.5±0 | 1126±31 | 848±29 | 232±5 | 48±0.5 |
| 118(BNLN-25) | 2.12±0.06 | 2.54±0.19 | 0.24 | 8.6± 0.5 | (0.0) | 24.5±0 | 72.5±0 | 1112± 8 | 834± 3 | 233±4 | 47±0.9 |
| 119(BNHC-25) | 2.12±0.06 | 2.61±0.17 | 0.23 | 69 ± 8 | 0.8 | 25.0±0 | 72.5±0.5 | 1111± 2 | 832± 2 | 233±3 | 47±0.6 |
| 120(BNHN-25) | 2.13±0.08 | 2.68±0.17 | 0.23 | 76 ± 8 | 0.0 | 24.5±0 | 72.5±0.5 | 1090±42 | 810±43 | 232±4 | 45±1.2 |
| 121(BELC-25) | 1.93±0.05 | 2.29±0.17 | 0.14 | 9.2± 0.5 | 0.8 | 24.5±0 | 72 ±0.5 | 765±19 | 488±16 | 232±5 | 48±0.3 |
| 122(BELN-25) | 1.89±0.06 | 2.27±0.21 | 0.13 | 9.2± 0.4 | 0.0 | 25.0±0 | 72.5±0 | 748±18 | 470±20 | 230±4 | 46±0.3 |
| 123(BEHC-25) | 1.91±0.10 | 2.27±0.19 | 0.14 | 69 ± 9 | 0.8 | 24.5±0 | 72.5±0.5 | 749±21 | 472±23 | 232±5 | 46±0.3 |
| 124(BEHN-25) | 1.89±0.04 | 2.21±0.21 | 0.14 | 78 ± 7 | 0.0 | 25.0±0 | 72.5±0 | 772± 9 | 495± 9 | 232±2 | 45±0.3 |
| 125(FNLC-25) | 1.91±0.07 | 11.76±1.40 | 0.28 | 9.9± 0.9 | (0.61) | 25.0±0 | 71.5±0.5 | 1268±18 | 993±18 | 229±2 | 48±0.5 |
| 126(FNLN-25) | 1.92±0.08 | 11.86±1.06 | 0.28 | 9.4± 0.5 | 0.0 | 25.0±0 | 71.5±0.5 | 1281±44 | 1007±43 | 229±2 | 46±0.8 |
| 127(FNHC-25) | 1.91±0.05 | 11.85±0.55 | 0.28 | 68 ±11 | 0.8 | 25.0±0 | 71 ±0.5 | 1269±17 | 989±20 | 233±4 | 47±0.7 |
| 128(FNHN-25) | 1.95±0.04 | 12.13±0.66 | 0.29 | 68 ± 6 | 0.0 | 25.0±0 | 71.5±0.5 | 1299±21 | 1018±26 | 230±5 | 47±0.5 |
| 129(FELC-25) | 1.80±0.06 | 10.19±1.26 | 0.16 | 9.2± 0.7 | 0.8 | 25.0±0 | 71.5±0.5 | 836±47 | 560±47 | 232±6 | 47±0.6 |
| 130(FELN-25) | 1.82±0.06 | 9.97±0.81 | 0.16 | 9.4± 0.8 | (0.0) | 24.5±0 | 72 ±0.5 | 841± 7 | 563± 9 | 230±2 | 45±0.5 |
| 131(FEHC-25) | 1.85±0.03 | 10.17±0.36 | 0.21 | 70 ± 8 | 0.8 | 24.1±0.5 | 71 ±0 | 959±22 | 679±22 | 230±3 | 47±0.7 |
| 132(FEHN-25) | 1.86±0.04 | 9.89±0.58 | 0.16 | 75 ± 8 | 0.0 | 25.0±0 | 71.5±0 | 840±13 | 563±11 | 230±2 | 45±0.2 |

(a) Measured at North Carolina State University, Department of Crop Science
(b) Measured at Kimberly-Clark Corporation
(c) CORESTA corresponds to cm³/min·cm² measured at 1 cbar.
(d) Nominal, except for those in parentheses which were determined by U.S.CPSC



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## Table 2-4. Measured Physical and Chemical Characteristics of Series 2 Experimental Cigarettes

| | Tobacco Analysis[a] | | | Paper variables | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Experimental Cigarette Designation | Total alkaloid (%) | Sugar (%) | Packing density ($mg/mm^3$) | Permeability[b] CORESTA[c] Outer | Inner | Embossed[e] | Circum. (mm) | Tobacco column length (mm) | Total cigarette weight (mg) | Tobacco weight (mg) | Filter weight (mg) | Paper weight (mg) Inner | Outer |
| 201 | 1.88 | 12.0 | 0.14 | 5.2 ± 0.6 | – | – | 21 ± 0.5 | 73 ± 0 | 583 ± 24 | 366 ± 24 | 171 ± 2 | – | 43 ± 0.6 |
| 202 | 1.97 | 12.5 | 0.16 | 6.4 ± 0.8 | – | – | 25 ± 0.5 | 72 ± 0 | 828 ± 14 | 566 ± 14 | 216 ± 3 | – | 45 ± 0.9 |
| 203 | 1.95 | 12.6 | 0.15 | 58. ± 5.3[d] | – | – | 25 ± 0.5 | 72 ± 0.5 | 784 ± 29 | 519 ± 25 | 216 ± 6 | – | 48 ± 0.4 |
| 204 | 1.95 | 12.5 | 0.16 | 87. ± 59 | – | YES | 24 ± 0.5 | 71.5 ± 0.5 | 798 ± 19 | 531 ± 17.6 | 218 ± 3 | – | 47 ± 0.5 |
| 205 | 1.90 | 12.4 | 0.19 | 160. ± 49.[d] | – | YES | 25 ± 0.5 | 71.5 ± 0.5 | 819 ± 6 | 549 ± 7.7 | 216 ± 1 | – | 47 ± 0.6 |
| 206 | 1.88 | 11.1 | 0.16 | 6.2 ± 1.2 | 7300 ± 700 | – | 25 ± 0.5 | 72 ± 0.5 | 848 ± 32 | 540 ± 20 | 213 ± 3 | 35 ± 0.7 | 46 ± 1.2 |
| 207 | 1.92 | 12.1 | 0.16 | 59. ± 12.[d] | 7700 ± 700 | – | 24.5 ± 0.5 | 72 ± 0.5 | 829 ± 11 | 530 ± 11 | 214 ± 3 | 35 ± 1.1 | 47 ± 1.3 |
| 208 | 1.97 | 12.5 | 0.16 | 84. ± 47. | 6800 ± 400 | YES | 25.5 ± 0 | 71.5 ± 0 | 836 ± 16 | 531 ± 18 | 219 ± 5 | 35 ± 0.7 | 46 ± 0.6 |
| 209 | 1.90 | 12.1 | 0.16 | 140. ± 33.[d] | 7200 ± 600 | YES | 25 ± 0.5 | 71.5 ± 0 | 819 ± 13 | 514 ± 9 | 218 ± 2 | 35 ± 0.9 | 48 ± 1.9 |

(a) Measured at North Carolina State University, Department of Crop Science
(b) Measured at Kimberly-Clark Corporation
(c) expressed in $cm^3/min \cdot cm^2 \cdot cbar$
(d) 4-6 CORESTA, electrostatically perforated to 60 CORESTA units
(e) Outer paper embossed

report is shown in Appendix 2-F. According to this report, the Burley tobacco was clearly as labelled. Some uncertainty arose about the contents of the cigarettes containing nominally 100 percent flue-cured tobacco. The analyst's guess was that they contained a 90/10 blend of flue-cured and Burley tobacco. (We have been told that tobacco analysis from cigarette specimens is a rather imprecise art [2-5].)

The cigarette and tobacco weights were affected by the Burley or flue-cured tobacco blend, tobacco packing density, and cigarette diameter. The non-expanded, flue-cured cigarettes were on average about 160 mg heavier than the cigarettes made from the Burley tobacco blend. However, the expansion process reduced this difference, in that, the expanded Burley cigarettes weighed about 30 percent less, and the expanded flue-cured cigarettes about 40 percent less than their non-expanded counterparts, indicating that flue-cured tobacco can be expanded more effectively than Burley. The 25 mm circumference cigarettes weighed about 30 percent more than the 21 mm circumference cigarettes.

In general, the weight values obtained by the Lorillard Laboratories (Tables 2-5 and 2-6) were often but not always higher than those obtained at NBS. The slightly higher weights might reflect a higher relative humidity in the Lorillard laboratories.

The packing densities of cigarettes containing expanded tobacco were about 1/2 to 2/3 of those containing non-expanded tobacco. They were higher for the non-expanded, flue-cured cigarettes than the comparable Burley cigarettes, but rather similar after expansion. The packing densities of 21 and 25 mm cigarettes were similar.

With respect to the data for the paper wrapping, the important information is in the treatment and permeability. The three measured citrate content results appear to be somewhat lower than specified. The permeability of the nominally 10 CORESTA (low porosity) papers and that of the nominally 75 CORESTA (high porosity) papers appear to be reasonably close to the specified values.

There appears to be no significant difference between the values for tar, nicotine, and carbon monoxide deliveries and puff counts supplied by the Lorillard Laboratories and the Federal Trade Commission.

### Series 2 Experimental Cigarettes

These nine cigarettes were all made from the same flue-cured expanded tobacco as the cigarettes in Series 1. They were covered with a paper, as described in Table 2-2, with lower permeability than the paper used in the Series 1 cigarettes. All but one cigarette were nominally 25 mm circumference; one was nominally 21 mm circumference. Some of the cigarettes had paper which had been made more permeable by electrostatic perforation and/or embossed paper, and some had a light, highly permeable inner wrapping between the cigarette paper and the tobacco column.

Table 2-4 shows that the cigarette, tobacco, and paper weights, as well as packing densities were quite similar, as expected. The exception was, of course, cigarette number

**Table 2-5. Physical Characteristics and Smoke Yields of Experimental Cigarettes, Series 1.** Data from Lorillard Laboratories

| CIGT[1] NO | CIGT DESC | LBR | LBR SD | MBR | MBR/LBR | C WT | C WT SD | PD | PD SD | NIC | NIC SD | TAR | TAR SD | CO | CO SD | PC | PC SD | TAR RE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | BNLC-21 | 5.79 | 0.34 | 54.9 | 9.48 | 0.873 | 0.0049 | 261.8 | 15.3 | 1.65 | 0.09 | 18.4 | 0.66 | 20.1 | 0.98 | 8.0 | 0.10 | 35.7 |
| 2 | BNLN-21 | 4.80 | 0.18 | 45.6 | 9.50 | 0.866 | 0.0082 | 245.8 | 9.8 | 1.93 | 0.02 | 21.6 | 0.96 | 19.4 | 0.13 | 8.0 | 0.22 | 33.4 |
| 3 | BNHC-21 | 7.42 | 0.36 | 71.5 | 9.64 | 0.882 | 0.0102 | 226.5 | 14.1 | 1.30 | 0.08 | 12.7 | 0.60 | 13.4 | 0.07 | 7.8 | 0.16 | 33.3 |
| 4 | BNHN-21 | 6.82 | 0.32 | 64.4 | 9.44 | 0.860 | 0.0073 | 221.7 | 19.2 | 1.47 | 0.04 | 15.1 | 0.62 | 11.7 | 0.62 | 7.9 | 0.15 | 31.9 |
| 5 | BELC-21 | 7.77 | 0.67 | 47.2 | 6.07 | 0.612 | 0.0050 * | 500.0 | 0.0 | 0.46 | 0.04 | 7.9 | 0.68 | 9.0 | 0.00 | 6.2 | 0.33 | 32.1 |
| 6 | BELN-21 | 6.58 | 0.60 | 39.8 | 6.05 | 0.613 | 0.0051 * | 500.0 | 0.0 | 0.61 | 0.04 | 10.1 | 0.71 | 10.7 | 0.00 | 6.5 | 0.33 | 35.2 |
| 7 | BEHC-21 | 9.99 | 1.16 | 59.6 | 5.97 | 0.605 | 0.0016 | 344.3 | 40.5 | 0.36 | 0.03 | 5.6 | 0.87 | 6.3 | 0.76 | 5.7 | 0.18 | 42.5 |
| 8 | BEHN-21 | 8.89 | 0.70 | 53.3 | 6.00 | 0.612 | 0.0054 | 382.8 | 46.9 | 0.40 | 0.02 | 6.5 | 0.57 | 6.0 | 0.43 | 6.3 | 0.24 | 40.0 |
| 9 | FNLC-21 | 4.46 | 0.28 | 49.4 | 11.08 | 0.984 | 0.0126 | 217.8 | 22.9 | 2.26 | 0.06 | 26.7 | 0.77 | 20.9 | 1.31 | 11.4 | 0.26 | 33.9 |
| 10 | FNLN-21 | 3.40 | 0.17 | 40.3 | 11.85 | 1.038 | 0.0012 | 254.9 | 20.5 | 2.54 | 0.35 | 28.3 | 1.38 | 18.7 | 0.35 | 12.7 | 0.37 | 39.0 |
| 11 | FNHC-21 | 5.30 | 0.38 | 62.3 | 11.75 | 1.037 | 0.0007 | 215.0 | 11.3 | 1.86 | 0.07 | 20.0 | 0.61 | 12.4 | 0.28 | 11.1 | 0.23 | 36.3 |
| 12 | FNHN-21 | 4.96 | 0.34 | 57.9 | 11.67 | 1.027 | 0.0068 | 202.7 | 8.6 | 1.84 | 0.12 | 19.0 | 1.52 | 15.8 | 0.28 | 10.7 | 0.33 | 36.6 |
| 13 | FELC-21 | 7.34 | 0.60 | 42.4 | 5.78 | 0.593 | 0.0063 | 252.7 | 32.5 | 1.03 | 0.06 | 13.4 | 0.61 | 12.4 | 0.57 | 6.1 | 0.27 | 35.0 |
| 14 | FELN-21 | 5.52 | 0.46 | 33.8 | 6.12 | 0.621 | 0.0041 | 288.0 | 22.7 | 1.40 | 0.05 | 18.0 | 0.62 | 14.1 | 0.48 | 6.9 | 0.17 | 37.2 |
| 15 | FEHC-21 | 8.99 | 0.70 | 55.2 | 6.14 | 0.617 | 0.0073 | 222.3 | 18.6 | 0.75 | 0.04 | 8.9 | 0.65 | 7.8 | 0.95 | 6.0 | 0.25 | 43.6 |
| 16 | FEHN-21 | 7.58 | 0.60 | 45.6 | 6.02 | 0.612 | 0.0032 | 219.0 | 19.0 | 0.96 | 0.02 | 11.4 | 0.42 | 7.6 | 0.51 | 6.5 | 0.17 | 41.3 |
| 17 | BNLC-25 | 5.84 | 0.34 | 72.5 | 12.41 | 1.140 | 0.0054 | 151.7 | 7.4 | 1.99 | 0.01 | 20.9 | 0.63 | 27.4 | 0.00 | 8.4 | 0.08 | 37.2 |
| 18 | BNLN-25 | 4.78 | 0.18 | 58.9 | 12.32 | 1.130 | 0.0059 | 155.7 | 5.0 | 2.19 | 0.15 | 25.3 | 0.37 | 26.6 | 0.00 | 8.8 | 0.08 | 34.5 |
| 19 | BNHC-25 | 7.60 | 0.41 | 93.1 | 12.25 | 1.127 | 0.0045 | 136.3 | 5.4 | 1.65 | 0.04 | 15.9 | 0.66 | 18.9 | 0.91 | 7.9 | 0.15 | 34.9 |
| 20 | BNHN-25 | 6.72 | 0.28 | 83.2 | 12.38 | 1.131 | 0.0055 | 135.6 | 6.3 | 1.83 | 0.09 | 17.4 | 0.38 | 15.1 | 1.17 | 8.1 | 0.24 | 35.6 |
| 21 | BELC-25 | 8.11 | 0.45 | 61.2 | 7.55 | 0.774 | 0.0023 | 259.4 | 29.3 | 0.73 | 0.03 | 12.1 | 0.49 | 16.0 | 0.40 | 5.8 | 0.14 | 44.2 |
| 22 | BELN-25 | 6.38 | 0.28 | 46.8 | 7.34 | 0.770 | 0.0041 | 254.9 | 27.2 | 1.00 | 0.03 | 15.5 | 0.36 | 16.0 | 0.52 | 6.3 | 0.14 | 40.8 |
| 23 | BEHC-25 | 10.63 | 0.78 | 78.2 | 7.36 | 0.759 | 0.0001 | 196.0 | 22.2 | 0.57 | 0.05 | 8.6 | 0.43 | 11.2 | 0.83 | 5.6 | 0.27 | 43.6 |
| 24 | BEHN-25 | 9.12 | 0.45 | 67.6 | 7.41 | 0.769 | 0.0061 | 186.8 | 12.4 | 0.72 | 0.03 | 10.2 | 0.78 | 9.6 | 0.74 | 6.2 | 0.00 | 37.9 |
| 25 | FNLC-25 | 4.05 | 0.15 | 61.7 | 15.23 | 1.341 | 0.0025 | 139.9 | 6.0 | 2.79 | 0.10 | 30.7 | 1.29 | 24.2 | 1.51 | 13.3 | 0.34 | 37.9 |
| 26 | FNLN-25 | 3.46 | 0.14 | 51.1 | 14.77 | 1.317 | 0.0024 | 134.0 | 7.4 | 3.06 | 0.11 | 35.0 | 0.60 | 22.8 | 0.52 | 13.6 | 0.49 | 33.9 |
| 27 | FNHC-25 | 5.08 | 0.18 | 75.5 | 14.86 | 1.314 | 0.0053 | 119.4 | 6.2 | 2.52 | 0.14 | 25.0 | 0.86 | 19.3 | 1.22 | 11.5 | 0.13 | 30.0 |
| 28 | FNHN-25 | 4.58 | 0.17 | 69.1 | 15.09 | 1.335 | 0.0010 | 116.5 | 4.8 | 2.75 | 0.11 | 27.2 | 2.13 | 16.9 | 1.10 | 12.1 | 0.22 | 36.7 |
| 29 | FELC-25 | 5.17 | 0.35 | 44.2 | 8.55 | 0.846 | 0.0053 | 178.9 | 39.5 | 1.62 | 0.01 | 18.9 | 0.81 | 16.8 | 0.81 | 7.8 | 0.08 | 44.2 |
| 30 | FELN-25 | 3.88 | 0.41 | 33.6 | 8.66 | 0.862 | 0.0039 | 192.6 | 22.5 | 2.06 | 0.09 | 24.0 | 0.81 | 19.4 | 1.42 | 9.1 | 0.13 | 40.2 |
| 31 | FEHC-25 | 6.43 | 0.85 | 61.9 | 9.63 | 0.936 | 0.0011 | 247.4 | 80.2 | 0.94 | 0.07 | 11.2 | 1.19 | 9.7 | 0.59 | 8.8 | 0.41 | 38.7 |
| 32 | FEHN-25 | 5.27 | 0.34 | 45.1 | 8.56 | 0.857 | 0.0049 | 161.4 | 13.9 | 1.45 | 0.07 | 16.3 | 0.56 | 11.0 | 0.60 | 8.3 | 0.30 | 39.4 |

LBR - linear burn rate, mm/min.
MBR - mass burn rate, mg/min.
C WT - cigarette weight, g
PD - pressure drop, mm $H_2O$
Nic - nicotine
PC - puff count
TAR RE - tar residue
nic, tar, and tar RE in mg
1 - correspond to 101-132, respectively

201 which was thinner and lighter. The electrostatic perforation increased the CORESTA permeability value to about 58, the embossing to about 85, and the combination of electrostatic perforation and embossing to 140 to 160. Visual inspection of the embossed paper indicated that the embossing caused small holes in the paper, and was rather uneven. The standard deviation of the permeability results for the embossed papers was much higher than that of the base and perforated-only papers, indicating poor control. The inner wrappers were very light and permeable.

There appeared to be no significant differences between the values for tar, nicotine, and carbon monoxide deliveries and puff counts supplied by the Lorillard Laboratories and the Federal Trade Commission.

**Table 2-6. Smoke Yields of Experimental Cigarettes, Series 2.** Data from Lorillard Laboratories

| CODE [1] | WEIGHT [2] | WEIGHT S.D. | PRESSURE DROP mm-H2O | PRESSURE DROP S.D. | TAR [3] | TAR S.D. | NICOTINE [3] | NICOTINE S.D. | CO [3] | CO S.D. | PUFF COUNT | PUFF COUNT S.D. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.2 | 0.613 | 0.0024 | 278 | 22.99 | 18.2 | 1.31 | 1.55 | 0.095 | 15.6 | 0.97 | 7.0 | 0.21 |
| 2.2 | 0.891 | 0.0011 | 260 | 28.36 | 20.0 | 0.74 | 1.80 | 0.074 | 18.4 | 0.72 | 10.3 | 0.47 |
| 3.2 | 0.858 | 0.0040 | 205 | 15.44 | 18.4 | 0.84 | 1.66 | 0.054 | 15.3 | 0.54 | 10.5 | 0.29 |
| 4.2 | 0.853 | 0.0041 | 191 | 23.31 | 14.2 | 0.36 | 1.26 | 0.050 | 9.8 | 1.03 | 11.8 | 0.26 |
| 5.2 | 0.856 | 0.0077 | 155 | 10.80 | 13.9 | 1.02 | 1.35 | 0.087 | 10.2 | 0.94 | 11.0 | 0.34 |
| 6.2 | 0.886 | 0.0020 | 259 | 35.14 | 22.5 | 0.75 | 1.88 | 0.053 | 22.2 | 0.26 | 9.7 | 0.33 |
| 7.2 | 0.867 | 0.0035 | 212 | 17.87 | 18.6 | 0.35 | 1.66 | 0.037 | 17.9 | 0.54 | 10.1 | 0.11 |
| 8.2 | 0.859 | 0.0064 | 207 | 19.61 | 17.2 | 0.50 | 1.45 | 0.010 | 15.1 | 0.86 | 10.1 | 0.29 |
| 9.2 | 0.861 | 0.0060 | 176 | 12.05 | 15.3 | 0.92 | 1.36 | 0.112 | 12.1 | 0.70 | 11.1 | 0.35 |

S.D.: STANDARD DEVIATION
1 : CORRESPOND TO 201-209, RESPECTIVELY
2 : EXPRESSED IN GRAMS
3 : EXPRESSED IN MILLIGRAMS

## Table 2-7. FTC Values for Tar, Nicotine, and Carbon Monoxide Yields and Puff Count of Series 1 Experimental Cigarettes

| Experimental cigarette designation | Tar (mg) | Nicotine (mg) | CO (mg) | Puff Count |
|---|---|---|---|---|
| 101 (BNLC-21) | 19 ± 0.8 | 1.4 ± 0.07 | 21 ± 0.7 | 7.7 ± 0.20 |
| 102 (BNLN-21) | 22 ± 0.3 | 1.6 ± 0.06 | 21 ± 0.2 | 8.0 ± 0.12 |
| 103 (BNHC-21) | 13 ± 0.7 | 1.2 ± 0.05 | 14 ± 0.6 | 7.4 ± 0.24 |
| 104 (BNHN-21) | 15 ± 0.6 | 1.3 ± 0.02 | 13 ± 0.5 | 7.4 ± 0.22 |
| 105 (BELC-21) | 9 ± 0.6 | 0.5 ± 0.06 | 11 ± 0.5 | 5.8 ± 0.12 |
| 106 (BELN-21) | 11 ± 0.7 | 0.6 ± 0.01 | 12 ± 0.3 | 6.0 ± 0.40 |
| 107 (BEHC-21) | 6 ± 0.7 | 0.4 ± 0.03 | 6 ± 0.7 | 5.8 ± 0.28 |
| 108 (BEHN-21) | 7 ± 0.5 | 0.5 ± 0.04 | 5 ± 0.4 | 5.6 ± 0.16 |
| 109 (FNLC-21) | 28 ± 1.1 | 2.3 ± 0.05 | 22 ± 1.9 | 11.2 ± 0.26 |
| 110 (FNLN-21) | 28 ± 0.9 | 2.4 ± 0.12 | 20 ± 1.0 | 12.8 ± 0.44 |
| 111 (FNHC-21) | 20 ± 0.9 | 1.9 ± 0.12 | 15 ± 1.9 | 10.4 ± 0.14 |
| 112 (FNHN-21) | 21 ± 1.4 | 1.9 ± 0.13 | 14 ± 0.5 | 11.4 ± 0.32 |
| 113 (FELC-21) | 14 ± 0.6 | 1.1 ± 0.06 | 13 ± 1.0 | 5.8 ± 0.32 |
| 114 (FELN-21) | 17 ± 0.5 | 1.4 ± 0.02 | 14 ± 0.9 | 6.6 ± 0.10 |
| 115 (FEHC-21) | 10 ± 0.4 | 0.8 ± 0.05 | 9 ± 0.1 | 5.8 ± 0.10 |
| 116 (FEHN-21) | 12 ± 0.7 | 1.0 ± 0.04 | 8 ± 0.6 | 6.4 ± 0.20 |
| 117 (BNLC-25) | 22 ± 0.8 | 1.7 ± 0.04 | 27 ± 0.9 | 8.4 ± 0.22 |
| 118 (BNLN-25) | 25 ± 0.7 | 1.9 ± 0.03 | 25 ± 0.6 | 8.8 ± 0.16 |
| 119 (BNHC-25) | 16 ± 0.3 | 1.4 ± 0.04 | 18 ± 1.3 | 7.7 ± 0.16 |
| 120 (BNHN-25) | 18 ± 1.0 | 1.6 ± 0.03 | 15 ± 1.5 | 8.4 ± 0.20 |
| 121 (BELC-25) | 12 ± 0.4 | 0.7 ± 0.01 | 15 ± 1.0 | 5.6 ± 0.16 |
| 122 (BELN-25) | 15 ± 0.8 | 0.9 ± 0.02 | 15 ± 1.5 | 6.2 ± 0.22 |
| 123 (BEHC-25) | 8 ± 0.9 | 0.5 ± 0.03 | 10 ± 0.9 | 5.4 ± 0.22 |
| 124 (BEHN-25) | 9 ± 0.7 | 0.6 ± 0.03 | 8 ± 0.9 | 5.8 ± 0.20 |
| 125 (FNLC-25) | 32 ± 1.0 | 2.7 ± 0.07 | 25 ± 1.3 | 13.0 ± 0.18 |
| 126 (FNLN-25) | 34 ± 1.2 | 2.8 ± 0.11 | 24 ± 1.0 | 13.8 ± 0.26 |
| 127 (FNHC-25) | 25 ± 0.9 | 2.3 ± 0.10 | 20 ± 0.6 | 11.2 ± 0.30 |
| 128 (FNHN-25) | 27 ± 0.9 | 2.4 ± 0.06 | 17 ± 1.2 | 11.2 ± 0.28 |
| 129 (FELC-25) | 19 ± 0.4 | 1.5 ± 0.04 | 17 ± 0.4 | 8.4 ± 0.28 |
| 130 (FELN-25) | 22 ± 0.6 | 1.8 ± 0.09 | 19 ± 0.4 | 8.8 ± 0.36 |
| 131 (FEHC-25) | 10 ± 1.1 | 0.8 ± 0.06 | 9 ± 0.6 | 10.4 ± 0.52 |
| 132 (FEHN-25) | 16 ± 0.7 | 1.4 ± 0.06 | 11 ± 0.9 | 8.4 ± 0.20 |

**Table 2-8. FTC Values for Tar, Nicotine, and Carbon Monoxide Yields and Puff Count of Series 2 Experimental Cigarettes**

| Experimental cigarette designation | Tar (mg) | Nicotine (mg) | CO (mg) | Puff Count |
|---|---|---|---|---|
| 201 | 19 ± 0.6 | 1.4 ± 0.10 | 19 ± 1.3 | 7.6 |
| 202 | 20 ± 0.07 | 1.6 ± 0.07 | 24 ± 1.5 | 10.0 |
| 203 | 18 ± 0.7 | 1.5 ± 0.09 | 19 ± 0.7 | 10.4 |
| 204 | 15 ± 1.1 | 1.2 ± 0.10 | 14 ± 1.5 | 11.4 |
| 205 | 13 ± 0.9 | 1.2 ± 0.08 | 14 ± 1.5 | 11.2 |
| 206 | 22 ± 0.2 | 1.6 ± 0.09 | 29 ± 1.1 | 9.0 |
| 207 | 19 ± 0.5 | 1.5 ± 0.11 | 23 ± 1.0 | 10.2 |
| 208 | 17 ± 0.6 | 1.4 ± 0.07 | 18 ± 1.1 | 10.6 |
| 209 | 15 ± 0.7 | 1.3 ± 0.07 | 16 ± 0.7 | 11.0 |

## Table 2-9. Upholstered Fabrics, Padding and Sheeting Used in the Investigation

| Material Number | Designation and Description | Abbrev. | Bolt Width (m) | Areal Density (g/m²)[a] | Yarn Density warp Tex[b] | Yarn Density warp $N_e$[c] | Yarn Density weft Tex[b] | Yarn Density weft $N_e$[c] | Thread Count #/2.54 cm warp | Thread Count #/2.54 cm weft | Yarn Ply warp | Yarn Ply weft | Fiber Content warp | Fiber Content weft | Fiber Content pile |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A. Materials Used in Bench-Scale Tests Only | | | | | | | | | | | | | | | |
| 1. | California Standard beige cotton velvet, 2x2 basket weave, warp pile | CA | 1.4 | 340 | 31 | 19 | 38 | 15 | 80 | 80 | 2 | 2 | cot[d] | cot | cot[e] |
| 2. | Denim blue warp, gray weft, reverse twill weave, sized | DEN | 1.5 | 480 | 101 | 6 | 98 | 6 | 66 | 40 | 1 | 1 | cot | cot | – |
| 3. | "Splendor" beige, plain weave, back-coated | SPL | 1.4 | 560 | 145 | 4 | 696 | 0.8 | 10 | 11 | 2 | 1 | cot | cot | – |
| 4. | "Haitian Cotton" natural cotton plain weave, variable thickness of weft yarns, backcoated | HA | 1.4 | 660 | 183 | 3 | 1159 | 0.5 | 14 | 10 | 2 | 1 | cot | cot | – |
| 5. | Duck natural, plain weave | DU | 1.3 | 360 | 118 | 5 | 96 | 6 | 50 | 35 | 2 | 2 | cot | cot | – |
| 6. | Sheeting | | 2.4 | 130 | 18 | 34 | 18 | 34 | 104 | 88 | 1 | 1 | cot | cot | – |
| B. Materials Used in Full-Scale and Comparative Bench-Scale Tests | | | | | | | | | | | | | | | |
| 7. | California Standard (see above specifications) | | | | | | | | | | | | | | |
| 8. | Velvet plain weave, cotton warp pile, backcoated | VEL | 1.4 | 525 | 68 | 9 | 68 | 9 | 44 | 36 | >60 | >60 | polye[f] | polye | cot[g] |
| 9. | "Splendor" (see above specifications) | | | | | | | | | | | | | | |
| 10. | Damask 1 pink, plain weave with float yarns to create small patterns, backcoated | DA1 | 1.4 | 200 | 36 | 16 | 125 | 5 | 136 | 51 | 2 | 2 | cot | cot | – |
| 11. | Damask red, plain weave with float yarns to create geometric pattern, backcoated | DA2 | 1.4 | 250 | 42 | 14 | 75 | 8 | 144 | 88 | 2 | 2 | cot | cot | – |
| 12. | Olefin black, plain weave, back-coated | OL | 1.4 | 180 | 272 | 2 | 272 | 2 | 20 | 20 | >30 | >30 | ole[h] | ole | – |
| C. Paddings Used in Bench-Scale Tests Only | | | | | | | | | | | | | | | |
| | Cotton batting No. 300 quality untreated | CB | – | 40[i] | | | | | | | | | | | |
| | Polyurethane foam HD 2045 | PU | – | 32[i] | | | | | | | | | | | |
| D. Padding Used in Full-Scale and Comparative Bench-Scale Tests | | | | | | | | | | | | | | | |
| | Cotton batting same as above | CB | – | 40[i] | | | | | | | | | | | |
| | Polyurethane foam same as above | PU | – | 32[i] | | | | | | | | | | | |
| | Welt cord | – | – | – | 5700 | | | | | | | | | | |

**Table 2-9.** (Continued)

| Material Number | Supplier | Address |
|---|---|---|
| 1. | Van Waters & Rogers | 16300 Shoemaker Avenue, Cerritos, CA 90701 |
| 2. | local supplier | |
| 3. | Douglas, Inc. | P.O. 701, Egg Harbor, NJ 08215 |
| 4. | local supplier | |
| 5. | Test Fabrics, Inc. | P.O. Drawer O, 200 Blackford Avenue, Middlesex, NJ 08846 |
| 6. | local supplier | |
| 7. | same as # 1 | |
| 8. | supplied by UFAC | |
| 9. | same as # 3 | |
| 10. | supplied by UFAC | |
| 11. | supplied by UFAC | |
| 12. | supplied by UFAC | |
| CB | B.C.F. Supply Company | 2335 W. Franklin Street, Baltimore, MD 21223 |
| PU | Leggett & Platt | P.O. Box 2024, High Point, NC 27261 |
| welt cord | supplied by UFAC | |

(a) to convert SI to pounds per square yard, multiply by 0.00184
(b) Tex = grams per 1000 meters
(c) $N_e$ = hanks per one pound, where one hank equals 840 yards
(d) cot = cotton
(e) pile weight to material weight ratio is 0.38
(f) polye = polyester
(g) pile weight to material weight ratio is 0.57
(h) ole = olefin
(i) bulk density, kilograms per cubic meter
(j) to convert SI to pounds per cubic foot, multiply by 0.063

## Table 2-10. Cation Content of Upholstery Fabrics and Cotton Batting

| | Elemental Analysis (PPM)[a] | | | |
|---|---|---|---|---|
| Material | $Na^+$ | $K^+$ | $Ca^{+2}$ | $Mg^{+2}$ |
| California Standard | 662 ± 25 | < 100 | 285 ± 13 | 94 ± 5 |
| Denim | 1033 ± 92 | 402 ± 42 | 617 ± 84 | 422 ± 41 |
| "Splendor" | 589 ± 100 | 4890 ± 351 | 755 ± 5 | 549 ± 17 |
| "Haitian Cotton" | 814 ± 32 | 6136 ± 520 | 28969 ± 1620 | 2876 ± 181 |
| Duck | 135 ± 25 | < 100 | 494 ± 52 | 146 ± 22 |
| Cotton Batting | 226 ± 21 | 5069 ± 260 | 919 ± 45 | 512 ± 55 |

(a) Values are the average of the replicate values reported in Appendix 2-G, i.e., the six values for the cotton batting and the three values for the remaining fabrics. The standard deviations were calculated from the replicates, since these values are a measure of the differences in the fabric bolt or cotton batting bundle. The standard deviations reported in Appendix 2-G are a measure of the technique's variability.

# Substrates

The upholstery fabrics and paddings were chosen by the Upholstered Furniture Action Council (UFAC) and NBS to represent a range of substrates which ignite with commercial cigarettes. They could thus be used to illustrate possible lower ignition propensities of the experimental and patented cigarettes.

## Fabrics

The upholstery fabrics and sheeting used in this study are described in Table 2-9. Fabrics of the same name in parts (A) and (B) of Table 2-9 are nominally the same, but come from different batches and thus may differ somewhat. The first three upholstery fabrics were used to test all of the cigarettes.

Upholstery fabric 4 was used to evaluate low ignition propensity cigarettes. Upholstery fabrics 1, 3 and 7 to 11 were used in the comparison of cigarette ignition propensities from bench-scale and full-size (chair) tests. Fabric 6 was used as a covering for cigarettes tested in the covered configuration. This is prescribed in many standard methods [e.g., 2-6, 7] and makes the test somewhat more severe and reproducible [2-8]. It also simulates a situation in which cigarettes are covered by loose clothing, sheets, etc. Fabric 5 was used for experiments in which alkali metal ions or soil were added.

Upholstery fabrics 1-3, which were used in the bench-scale study of all cigarettes and also for the work reported in Section 4, and fabrics 4 and 5 were analyzed for $Na^+$, $K^+$, $Mg^{+2}$, and $Ca^{+2}$ content by the Health Sciences Laboratory, U.S. Consumer Product Safety Commission. A summary of the data is shown in Table 2-10. The analytical procedure and raw data are included in Appendix 2-G.

## Padding

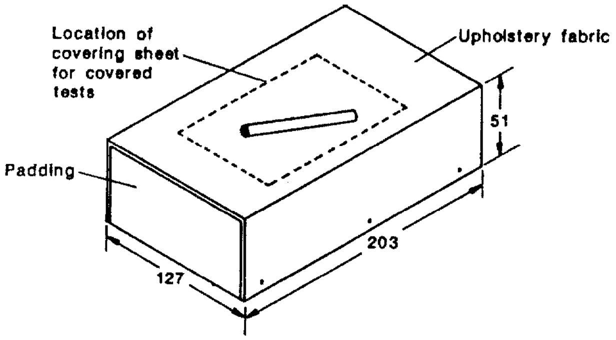
Two padding materials together with the above fabrics, were used in all evaluations. The paddings were non-fire retardant-treated (a) cotton batting and (b) HD 2045, Leggett and Platt polyurethane foam[5], both purchased at BCF Supply Co., 2335 W. Franklin St., Baltimore, MD. The cotton batting was analyzed in the same manner as the fabrics for $Na^+$, $K^+$, $Mg^{+2}$, and $Ca^{+2}$ content. The results are shown in Table 2-10. Previous results on the ion content of the polyurethane foam [2-1] showed such a small ion content that the analysis was not repeated for this study. Additional information on the padding is also presented in Table 2.9.

## Mockup Configurations

The mockup configurations used in this investigation were flat, crevice, or crevice with welt cord. In some cases the smoldering cigarette was covered with a piece of 100% cotton sheeting (fabric 6). The configurations are shown in Figure 2-1.

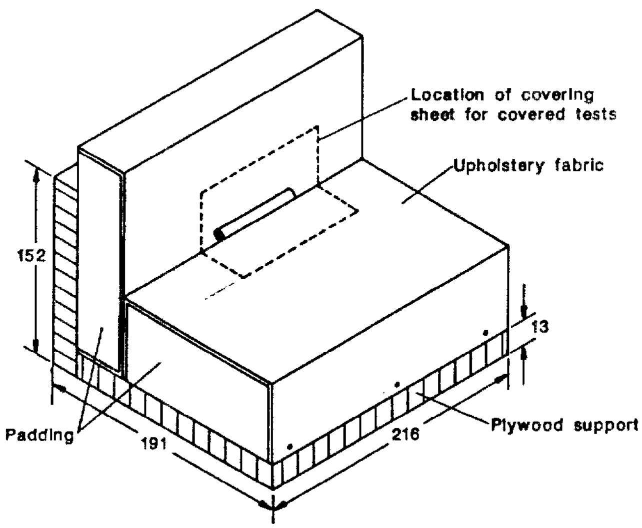
[5] *Certain commercial equipment, instruments, and materials are identified in this report to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment are necessarily the best available for the purpose.*

## Figure 2-1. Mockup Configurations

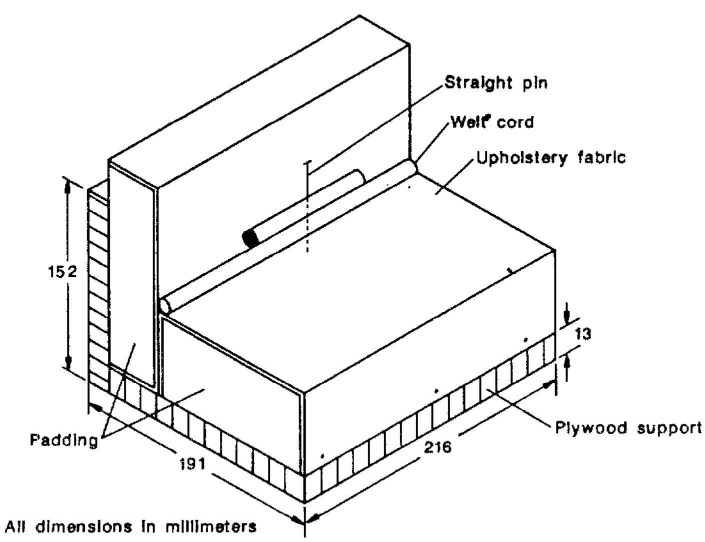



(a) Flat

All dimensions in millimeters




(b) Crevice (same size substrates as flat)




(c) Crevice w/ welt cord (same size substrates as flat)

# Chairs

The chairs used in the full-scale investigation of the ignition propensity of the experimental cigarettes were made under the supervision of UFAC by a commercial manufacturer. The width, depth, and height of the chairs were 750, 838 and 813 mm (29.5, 33 and 32 in.), respectively. They were constructed from the same wooden framing, webbing, and decking materials. The skirt was omitted. The sides were straight and the back was slightly inclined. Each chair was provided with two seat cushions. The chairs were constructed with the upholstery fabrics and paddings mentioned in Table 2-9 B and D. The 10 California Standard chairs were padded entirely with cotton batting; the 10 "Splendor" chairs were padded entirely with polyurethane padding. The eight each of the damask, heavy velvet, and olefin chairs contained polyurethane padding in the seat cushions and back and cotton batting in the arms. Four of each chair were provided without a welt cord and four were provided with a welt cord, with the exception of those prepared with California Standard fabric and "Splendor"; in these cases two additional chairs without welt cord were supplied for preparatory experiments. The damask chairs were supplied with two different fabrics varying slightly in weight.

Figure 2-2 shows four of the chairs arranged in the burn room prior to testing.

**Figure 2-2. Typical Chairs Used in the Full-Scale Tests Arranged in the Burn Room**

# References for Section 2


[2-1] Krasny, J. F. and Gann, R. G., "Relative Propensity of Selected Commercial Cigarettes to Ignite Soft Furnishings Mockups," NBSIR 86-3421, U.S. National Bureau of Standards, Gaithersburg, MD, 1986.

[2-2] Pillsbury, H. C., Bright, C. C., O'Connor, K. J., and Irish, F. W., "Tar and Nicotine in Cigarette Smoke," Journal of the AOAC, 52, 3 (1969).

[2-3] Federal Register, 45, no. 134, July 10, 1980.

[2-4] Harvey, W. R., Stahr, H. M., Smith, W. C., "Automated Determination of Reducing Sugars and Nicotine Alkaloids on the Same Extract of Tobacco Leaf," Tobacco Science, 13, 13 (1969).

[2-5] Samfield, M., Personal Communication, April, 1986.

[2-6] Important Information from UFAC (Test Methods), Upholstered Furniture Action Council, High Point, NC (1985).

[2-7] The Business and Institutional Furniture Manufacturer's Association First Generation Voluntary Upholstered Furniture Standard for Business and Institutional Markets, BIFMA, Grand Rapids, MI (1980).

[2-8] Loftus, J.L., Back-Up Report for the Proposed Standard for the Flammability (Cigarette Ignition Resistance) of Upholstered Furniture, PFF 6-76, Appendix G1, NBSIR 78-1438, [U.S.] Nat. Bur. Stand., (1978).

# Appendix 2-A

Lorillard

DR. A. W. SPEARS
EXECUTIVE VICE PRESIDENT
OPERATIONS & RESEARCH

November 4, 1985

DR. GIL ESTERLE
DR. ALLEN KASSMAN
DR. PRESTON LEAKE
MR. BILL OWEN
DR. ALAN RODGMAN
DR. FRED SCHULTZ

Gentlemen:

I believe that we have everything in place for the manufacture of the National Bureau of Standards samples. However, there have been a few small changes in specifications since my prior memos, and I think it worthwhile to repeat everything in this memo so that all the information is set forth in one place.

I am also including in this memo sample designations that I ask the manufacturers and the suppliers to follow. In addition, each of the materials that you ship should contain the following label on the shipping container: Technical Study Group Materials - Cigarette Safety Act. In this way, materials will not be confused with any other sample materials that may be arriving at the same receiving point.

Reynolds has agreed to manufacture the filter rods for all 21 mm circumference cigarettes and will supply Philip Morris with about 40,000 108 mm rods. American has agreed to manufacture the filter rods for the 25 mm circumference cigarettes and will supply Brown & Williamson with about 40,000 108 mm filter rods. Individual tows, plug wraps, and plasticizer levels are to be selected by the manufacturer.

Ecusta will supply the cigarette papers in partial bobbin lengths of 4,000 m. One bobbin each of the following cigarette paper designations, as shown on the attached table, will be shipped to both American and Brown & Williamson: LN27, LC27, HN27, and HC27. One bobbin each of the following cigarette paper designations, LN23, LC23, HN23, and HC23, will be shipped to both Philip Morris and Reynolds.

Lorillard will supply the tobacco and will ship 600 pounds each of tobacco designations BN and BE, per the attached table, to both American and Philip Morris. Six hundred (600) pounds each of tobacco designations FN and FE will be shipped to both Brown & Williamson and Reynolds.

Lorillard will supply the tipping paper with no bobbin designation as shown in the attached table. Each manufacturer will receive one bobbin of 64 mm x 2700 m.

For those manufacturers that choose to package cigarettes in individual packs of 20, the numerical pack designation shown in the attached table should be used to identify the sample. Cases, trays, or similar packaging materials should show the box designation shown in the attached tables for purposes of sample identification.

Cigarette tobacco is being shipping at a moisture content that is suitable for the direct manufacture of cigarettes.

Lorillard has made some filling value measurements on the tobacco and will calculate a cigarette tobacco weight. Bear in mind that there are some errors in making this estimate, and this will not necessarily be the exact weight that you will need to manufacture acceptable cigarettes in the commercial firmness range. It should, however, be a good starting point. We now have individual names and shipping addresses for the materials. They are as follows:

Mr. Leonard Tilley
Manager, Reidsville Branch
American Tobacco Company
301 North Scales Street
Reidsville, NC 27320

Mr. B. A. Bandy/Esterle
Brown & Williamson Tobacco Corporation
Development Center
Gate 21, Dock 10F
McCloskey South of Lee
Louisville, KY 40210

Cigarette paper and tipping paper only should be sent to:

Mr. James Crichton/Kassman
Philip Morris Operations Center
Building A1-E
2001 Walmsley Blvd.
Richmond, VA 23234

The shipping point for tobacco and filter rods to Philip Morris will be designated a little later.

Mr. Ronald Pegram
R. J. Reynolds Tobacco Company
Bowman Gray Technical Center
Building 61112
Reynolds Boulevard
Winston-Salem, NC 27102

The National Bureau of Standards also desires 1-2 pound samples of each of the cut tobaccos. These will be shipped by Lorillard directly to NBS.

All tobacco samples will be shipped this week. I also understand that all paper samples will be shipped this week. It, therefore, seems that all materials should be received no later than the first part of next week.

Sincerely,

Xc: Dr. Richard Gann
Attachments
AWS/hsj

2525 East Market Street
Greensboro, North Carolina 27401

## CUT TOBACCO DESIGNATIONS

| | Box Designation |
|---|---|
| Burley Non-Expanded, 60 cuts/inch | BN |
| Burley Expanded, 30 cuts/inch | BE |
| Flue-cured Non-Expanded, 60 cuts/inch | FN |
| Flue-cured Expanded, 30 cuts/inch | FE |

## CIGARETTE PAPER DESIGNATIONS

### 23 mm

| | Bobbin Designation |
|---|---|
| Low Porosity, No Additive (10 CORESTA Units) | LN-23 |
| Low Porosity, Citrate (10 CORESTA Units, 0.8% Citrate) | LC-23 |
| High Porosity, No Additive (75 CORESTA Units) | HN-23 |
| High Porosity, Citrate (75 CORESTA Units, 0.8% Citrate) | HC-23 |

### 27 mm

| | |
|---|---|
| Low Porosity, No Additive (10 CORESTA Units) | LN-27 |
| Low Porosity, Citrate (10 CORESTA Units, 0.8% Citrate) | LC-27 |
| High Porosity, No Additive (75 CORESTA Units) | HN-27 |
| High Porosity, Citrate (75 CORESTA Units, 0.8% Citrate) | HC-27 |

## TIPPING PAPER DESIGNATION

| | Bobbin Designation |
|---|---|
| 64 mm, White, 36.5 $gm/m^2$ | None |

## FILTER ROD DESIGNATION

| | Box Designation |
|---|---|
| 20.8 mm x 108 mm, PD 270 mm | FR-21 |
| 24.7 mm x 108 mm, PD 270 mm | FR-25 |

Table 2-A-1. Cigarette Manufacturer's Description of Series 1, 21 mm Experimental Cigarettes

CIGARETTE DESIGNATIONS

21 mm Circumference

| | Box Designation | Pack Designation |
|---|---|---|
| Burley-Non-Expanded-Low Porosity Citrate | BNLC-21 | 1 |
| Burley-Non-Expanded-Low Porosity-No Additive | BNLN-21 | 2 |
| Burley-Non-Expanded-High Porosity-Citrate | BNHC-21 | 3 |
| Burley-Non-Expanded-High Porosity-No Additive | BNHN-21 | 4 |
| Burley-Expanded-Low Porosity-Citrate | BELC-21 | 5 |
| Burley-Expanded-Low Porosity-No Additive | BELN-21 | 6 |
| Burley-Expanded-High Porosity-Citrate | BEHC-21 | 7 |
| Burley-Expanded-High Porosity-No Additive | BEHN-21 | 8 |
| Flue-Cured-Non-Expanded-Low Porosity-Citrate | FNLC-21 | 9 |
| Flue-Cured-Non-Expanded-Low Porosity-No Additive | FNLN-21 | 10 |
| Flue-Cured-Non-Expanded-High Porosity-Citrate | FNHC-21 | 11 |
| Flue-Cured-Non-Expanded-High Porosity-No Additive | FNHN-21 | 12 |
| Flue-Cured-Expanded-Low Porosity-Citrate | FELC-21 | 13 |
| Flue-Cured-Expanded-Low Porosity-No Additive | FELN-21 | 14 |
| Flue-Cured-Expanded-High Porosity-Citrate | FEHC-21 | 15 |
| Flue-Cured-Expanded-High Porosity-No Additive | FEHN-21 | 16 |

Table 2-A-2. Cigarette Manufacturer's Description of Series 1, 25 mm Experimental Cigarettes

CIGARETTE DESIGNATIONS

25 mm Circumference

| | Box Designation | Pack Designation |
|---|---|---|
| Burley-Non-Expanded-Low Porosity-Citrate | BNLC-25 | 17 |
| Burley-Non-Expanded-Low Porosity-No Additive | BNLN-25 | 18 |
| Burley-Non-Expanded-High Porosity-Citrate | BNHC-25 | 19 |
| Burley-Non-Expanded-High Porosity-No Additive | BNHN-25 | 20 |
| Burley-Expanded-Low Porosity-Citrate | BELC-25 | 21 |
| Burley-Expanded-Low Porosity-No Additive | BELN-25 | 22 |
| Burley-Expanded-High Porosity-Citrate | BEHC-25 | 23 |
| Burley-Expanded-High Porosity-No Additive | BEHN-25 | 24 |
| Flue-Cured-Non-Expanded-Low Porosity-Citrate | FNLC-25 | 25 |
| Flue-Cured-Non-Expanded-Low Porosity-No Additive | FNLN-25 | 26 |
| Flue-Cured-Non-Expanded-High Porosity-Citrate | FNHC-25 | 27 |
| Flue-Cured-Non Expanded-High Porosity-No Additive | FNHN-25 | 28 |
| Flue-Cured-Expanded-Low Porosity-Citrate | FELC-25 | 29 |
| Flue-Cured-Expanded-Low Porosity-No Additive | FELN-25 | 30 |
| Flue-Cured-Expanded-High Porosity-Citrate | FEHC-25 | 31 |
| Flue-Cured-Expanded-High Porosity-No Additive | FEHN-25 | 32 |

Burley Blend

| | |
|---|---|
| Flyings | 19.7% |
| Lugs | 17.3% |
| Leaf | 47.5% |
| Tips | 7.4% |
| Invert Sugar | 5.3% |
| Glycerine | 2.8% |
| Total | 100.0% |

Flue-Cured Blend

| | |
|---|---|
| Primings | 13.8% |
| Lugs & Cutters | 24.3% |
| Smoking . | 10.6% |
| Leaf | 43.2% |
| Invert Sugar | 5.3% |
| Glycerine | 2.8% |
| Total | 100.0% |

All cigarettes will be manufactured to the following specifications:

| | |
|---|---|
| Quantity: | 10,000 |
| Length | 100 mm |
| Type: | Filter |
| Filter Length: | 27 mm |
| Tipping Paper Length: | 32 mm |
| Circumference: | ± 0.1 mm of specification |
| Cut Width: | As specified |
| Firmness: | Within commercial limits of acceptance |
| Moisture: | Commercial standards |
| Weight: | ± 1.5% of mean |
| Filter Tip Pressure Drop (Encapsulated): | 67.5 mm |
| Filter Tow Characteristics: | A commercial standard |
| Plasticizer Level: | Commercial range |
| Plasticizer: | Commercial product |

Packaging: Suitable to avoid moisture loss and damage in shipment.

Shipping: Mr. John Krasny
National Bureau of Standards
Building 224, Room A363
Quince Orchard Road
Gaithersburg, Maryland 20899

PROBLEMS WITH MATERIALS

| | |
|---|---|
| Cigarette Papers: (Ecusta) | Bill Owen (704-877-2311) or Wayne McCarty (704-877-2211) |
| Tipping Paper: (Lorillard) | Fred Schultz (919-373-6602) |
| Tobacco: (Lorillard) | Fred Schultz (919-373-6602) |
| Filter Rods: | Preston Leake (804-748-4561) of American Tobacco or Alan Rodgman (919-773-4269) of Reynolds |
| Miscellaneous: (Lorillard) | Alex Spears (919-373-6776) |

# Appendix 2-B

Lorillard

DR. A. W. SPEARS
EXECUTIVE VICE PRESIDENT
OPERATIONS & RESEARCH
(919) [illegible]

October 23, 1986

Dr. Jim Charles
Dr. Preston Leake
Dr. Alan Rodgman
Dr. Fred Schultz

Gentlemen:

I believe that I now have everything in place for the manufacture of the second series of cigarettes for the National Bureau of Standards in relation to the Technical Study Group activities.

Reynolds has agreed to manufacture one cigarette of 21 mm circumference, designated as Sample 1.2 in the accompanying material, which is a replicate of Cigarette #16 as described in my memo of November 4, 1985 except for the cigarette paper. Lorillard will manufacture eight cigarettes, and I have procured two from the National Cancer Institute. The samples will be supplied in quantities of 2,000 each and shipped no later than November 14 to the attention of:

Mr. John Krasny
National Bureau of Standards
Building 224, Room A363
Quince Orchard Road
Gaithersburg, MD 20899

Mr. Ronald Pegram will be responsible for the manufacture of the Reynolds sample, and Dr. Fred Schultz will be responsible for the manufacture of the Lorillard samples. Lorillard will ship 300 lbs. of cut tobacco to RJR for manufacture of Sample 1.2.

The procured samples were obtained from the National Cancer Institute archives and were prepared under the NCI Smoking and Health Program, the Second Set of Experimental Cigarettes. Code #46 was made from a synthetic smoking material filler known as NSM consisting of heat treated cellulose and sodium carboxymethyl cellulose. Code #43 was made from a synthetic filler from Celanese Corporation consisting of inorganic materials and sodium carboxymethyl cellulose. Both filler materials contain an added 2.8% glycerine and 5.3% invert sugar. Cigarette specifications were 85 mm length, 25 mm circumference, 26 CORESTA Units paper porosity, and an 0.85 citrate level in the cigarette paper.

2525 East Market Street
Greensboro North Carolina 27401

Sample Specifications

Expanded Flue-Cured Blend (FE)

| | |
|---|---|
| Primings | 13.8% |
| Lugs & Cutters | 24.3% |
| Smoking | 10.6% |
| Leaf | 43.2% |
| Invert Sugar | 5.3% |
| Glycerine | 2.8% |
| Total | 100.0% |

| | |
|---|---|
| Quantity | 2,000 cigarettes |
| Length | 100 mm |
| Type | Filter |
| Filter Length | 27 mm |
| Tipping Paper | 64 mm, white, 36.5 gm/m$^2$ |
| Circumference | ± 0.1 mm of specification |
| Cut Width | 30 cuts/inch |
| Firmness | Within commercial limits |
| Moisture | Commercial standard |
| Weight | ± 1.5% of mean |
| Filter Tip Pressure Drop/Encapsulated | 67.5 mm |
| Filter Rod | As specified - 24.7 mm x 108 mm, PD 270 mm or 20.8 mm x 108 mm, PD 270 mm |
| Filter Tow Characteristics | Commercial Standard |
| Plasticizer | Commercial product/commercial range |
| Cigarette Paper | No burn additives<br>Porosity: as specified<br>Dimensions: as specified |
| Packaging | Suitable to avoid moisture loss and damage during shipment. |
| Markings | Each packaging unit to be clearly marked with sample number |

Sincerely,

A. W. Spears

Xc: Dr. Richard Gann
Mr. Ron Pegram

AWS/hsj

Table 2-B-1. Cigarette Manufacturer's Description of Series 2 Experimental Cigarettes

| Sample | Blend | Circumference | Paper (Outer) | Paper (Inner) | Construction |
|---|---|---|---|---|---|
| 1.2 | FE | 21 | 4-6 CORESTA Units/ 23.5 mm | None | Single Wrap |
| 2.2 | FE | 25 | 4-6 CORESTA Units/ 27.5 mm | None | Single Wrap |
| 3.2 | FE | 25 | 4-6 CORESTA Unit Base Electrostatically Perforated to 60 CORESTA Units/27.5 mm | None | Single Wrap |
| 4.2 | FE | 25 | 4-6 CORESTA Units Embossed/27.5 mm | None | Single Wrap |
| 5.2 | FE | 25 | 4-6 CORESTA Units Electrostatically Perforated to 60 CORESTA Units/Embossed/ 27.5 mm | None | Single Wrap |
| 6.2 | FE | 25 | 4-6 CORESTA Units/ 27.5 mm | 7000 CORESTA Microporous Structure/ 25 mm | Double Wrap |
| 7.2 | FE | 25 | 4-6 CORESTA Unit Base Electrostatically Performated to 60 CORESTA Units/27.5 mm | 7000 CORESTA Microporous Structure/ 25 mm | Double Wrap |
| 8.2 | FE | 25 | 4-6 CORESTA Units Embossed/27.5 mm | 7000 CORESTA Microporous Structure/ 25 mm | Double Wrap |
| 9.2 | FE | 25 | 4-6 CORESTA Units Electrostatically Perforated to 60 CORESTA Units/Embossed/ 27.5 mm | 7000 CORESTA Microporous Structure/ 25 mm | Double Wrap |

# Appendix 2-C



**CONSUMER PRODUCT SAFETY COMMISSION**

**Interagency Committee on Cigarette and Little Cigar Fire Safety; Request for Samples of Patented, Non-Commercial Cigarettes for Ignition Propensity Testing**

**AGENCY**: Interagency Committee on Cigarette and Little Cigar Fire Safety.

**ACTION**: Notice.

**SUMMARY**: The Technical Study Group on Cigarette and Little Cigar Fire Safety invites inventors of cigarettes, which are not produced commercially but which are claimed to have reduced propensity to ignite upholstered furniture and mattresses, to submit samples of such cigarettes for ignition propensity testing. A description of the testing program and how inventors may participate follows.

**DATE**: Inventors who desire to participate in this testing program should submit samples of cigarette inventions and the information specified in this notice not later than September 30, 1986.

**ADDRESS**: Samples and information concerning cigarette inventions should be sent to: Dr. Richard G. Gann, Center for Fire Research, National Bureau of Standards, Gaithersburg, Maryland 20899.

**FOR FURTHER INFORMATION CONTACT**: Mrs. Tawanna Segears, Office of Program Management, Consumer Product Safety Commission, Washington, DC 20207; telephone: (301) 492-6554.

**SUPPLEMENTARY INFORMATION**: The Cigarette Safety Act of 1984 (Pub. L. 98-567, 98 Stat. 2925, October 30, 1984) created the Technical Study Group on Cigarette and Little Cigar Fire Safety (TSG) to investigate the technical and commercial feasibility of developing cigarettes and little cigars with minimum propensity to ignite upholstered furniture and mattresses. The TSG has developed an ignition propensity test and has tested some commercial cigarettes. The TSG also has decided to test the ignition propensity of some cigarettes which are not commercially available but which are claimed by their inventors to have less propensity than commercially available cigarettes to ignite upholstered furniture and mattresses. A limited cigarette ignition propensity testing program will be conducted by the Center for Fire Research at the National Bureau of Standards (NBS) at no charge by NBS to inventors whose inventions are selected for testing. Testing will be blind to the extent possble. Cigarette inventions which are patented or for which a patent has been filed will be candidates for testing. *Cigarette inventions for which a patent has not been issued or for which a patent application has not been filed as of the date of this Federal Register Notice, will not be tested.*

If an inventor desires to have his or her cigarette invention considered for testing on this program, the inventor must:

1. Select the single embodiment of his or her patent(s) believed to be most effective for consideration.

2. Submit documents which show that a patent has been issued or that the application for a patent has been filed.

3. Supply information as to the specific nature of the particular modification or additive employed in the cigarette invention *in quantitative terms*.

4. Provide evidence of significantly reduced propensity of the cigarette invention to ignite substrates found in mattresses and upholstered furniture.

5. Provide free of charge 300 invention cigarettes and 300 control cigarettes that are identical to the invention cigarettes except for the feature that comprises the effective ignition repression. The patented cigarettes and the control cigarettes should be clearly differentiated *on their packages*. The cigarettes should be packed so as to safeguard against damage during transport and should identify a person to contact if the shipment has been damaged.

6. Supply uniformity data (mean value plus standard deviation) for both the patented and control cigarettes with regard to the following properties:

cigarette mass
cigarette length and diameter
mass burning rate (in air)
magnitude of modification (e.g., concentration of additive)

Additionally, the TSG requests inventors submitting cigarettes for testing to provide information showing the absence of any obvious toxicity problems associated with the invention, and an analysis of the tar, nicotine, and carbon monoxide content of the smoke produced by the cigarette invention. However, the failure to provide this information will not preclude consideration of the cigarette invention for testing.

Samples of the cigarette invention, control cigarettes, and the information described above must be received by Dr. Richard G. Gann, Center for Fire Research, National Bureau of Standards, Gaithersburg, Maryland 20899, not later than September 30, 1986. *Materials received after September 30, 1986, will not be accepted.*

Inventors who submit their cigarettes for consideration as candidates for testing are advised that there will be absolutely no payment or reimbursement for the samples of cigarettes provided for testing. These samples will not be returned. Further, submission of test sample cigarettes which meet the criteria above does not necessarily mean that the sample cigarettes will be selected for testing. Selection of cigarette inventions for testing will be made by the TSG, whose decision will be final. While the TSG desires to test all cigarette inventions meeting the criteria set forth above, lack of funds, time constraints and other factors may limit the amount of testing which can be done.

The results of this testing program will be included in the TSG's final report to Congress. The TSG will not report results of testing individual cigarette inventions to patent holders. The TSG intends to report results of this testing program in a format which will not disclose results obtained from any individual cigarette invention. Selection of any cigarette invention for testing in this program does not constitute any form of endorsement or approval of the invention by the government of the United States.

Dated: June 3, 1986.

**Colin B. Church,**

*Federal Employee Designated by the Interagency Committee on Cigarette and Little Cigar Fire Safety.*

[FR Doc. 86-13483 Filed 6-13-86; 8:45 am]

BILLING CODE 6355-01-M



**CONSUMER PRODUCT SAFETY COMMISSION**

**Interagency Committee on Cigarette and Little Cigar Fire Safety; Ignition Propensity Testing of Patented, Non-Commercial Cigarettes**

**AGENCY:** Interagency Committee on Cigarette and Little Cigar Fire Safety, CPSC.

**ACTION:** Notice.

**SUMMARY:** In the Federal Register of June 16, 1986 (51 FR 21790), the Technical Study Group on Cigarette and Little Cigar Fire Safety (TSG) invited inventors of cigarettes which are not produced commercially but which are claimed to have reduced propensity to ignite upholstered furniture and mattresses to submit samples of such cigarettes for ignition propensity testing. That notice described the testing program and requirements for consideration of cigarette inventions as candidates for testing in this program. That notice specified that only cigarette inventions for which a patent had been issued or for which a patent application had been filed by June 16, 1986, would be eligible for consideration as candidates for testing in this program. The TSG has revised its criteria for selection of candidate inventions to include any cigarette invention for which a patent has been issued or for which a patent application has been filed by September 30, 1986.

**FOR FURTHER INFORMATION CONTACT:** Colin B. Church, Office of Program Management, Consumer Product Safety Commission, Washington, D.C. 20207; telephone: (301) 492-6554.

Dated: July 18, 1986.

**Colin B. Church,**

*Federal Employee Designated by the Interagency Committee on Cigarette and Little Cigar Fire Safety.*

[FR Doc. 86-17348 Filed 7-31-86; 8:45 am]

BILLING CODE 6355-01-M

# Appendix 2-D

Kimberly-Clark

Specialty Products

2 September 1986

Dr. Richard G. Gann
Chairman, Technical Study Group
National Bureau of Standards
Gaithersburg, Maryland 20899

Dear Dick:

We received from you the samples of the thirty-two experimental cigarettes for which we were contracted to determine the permeability of the paper. The work was performed under your Department of Commerce Reference Number: 41 USC 252 C03 and your Order Number: 43NANB617264. The analyses have been completed and the data are summarized on the attached sheet.

A word of explanation about the data. We removed the paper from five cigarettes chosen at random from each of the thirty-two packets. The permeability of each swatch was determined using CORESTA Recommended Method No. 3 [Determination of the air permeability of cigarette paper, CORESTA Information Bulletin, 1975 (3,4)] and reported as the velocity of air (in centimeters per minute) drawn through the paper at a pressure differential of one centibar (ten centimeters of water). In most cases, we made ten measurements, two on each swatch. For some of them we added an extra determination or so to beef up the statistics. In the table are listed the identification number of each item, the permeability of the wrapper, the standard deviation, and the number of measurements made.

You will receive our invoice mailed under separate cover.

Best regards.

Sincerely,

Charles F. Mattina

cc: Mr. John Krasny
National Bureau of Standards
Room A363, Building 224
Route 270 and Quince Orchard Road
Gaithersburg, Maryland 20899

CFM:86-200

Table 2-D-1. Paper Permeability of Series 1 Experimental Cigarettes Determined by Kimberly-Clark

| Item No. | Permeability (cm/min) | Standard deviation (cm/min) | N |
|---|---|---|---|
| 1 | 8.9 | 0.5 | 10 |
| 2 | 7.8 | 0.5 | 10 |
| 3 | 75. | 10. | 10 |
| 4 | 66. | 7. | 13 |
| 5 | 9.4 | 0.7 | 10 |
| 6 | 8.2 | 0.5 | 10 |
| 7 | 70. | 10. | 15 |
| 8 | 69. | 10. | 15 |
| 9 | 8.9 | 0.6 | 10 |
| 10 | 8.5 | 0.5 | 10 |
| 11 | 67. | 7. | 11 |
| 12 | 67. | 6. | 13 |
| 13 | 9.2 | 0.6 | 10 |
| 14 | 8.6 | 0.7 | 10 |
| 15 | 68. | 5. | 10 |
| 16 | 68. | 6. | 11 |
| 17 | 9.4 | 0.8 | 10 |
| 18 | 8.6 | 0.5 | 10 |
| 19 | 69. | 8. | 14 |
| 20 | 76. | 8. | 12 |
| 21 | 9.2 | 0.5 | 10 |
| 22 | 9.2 | 0.4 | 10 |
| 23 | 69. | 9. | 11 |
| 24 | 78. | 7. | 16 |
| 25 | 9.9 | 0.9 | 10 |
| 26 | 9.4 | 0.5 | 10 |
| 27 | 68. | 11. | 13 |
| 28 | 68. | 6. | 10 |
| 29 | 9.2 | 0.7 | 10 |
| 30 | 9.4 | 0.8 | 10 |
| 31 | 70. | 8. | 11 |
| 32 | 75. | 8. | 13 |

Kimberly-Clark

Specialty Products

21 January 1987

Mr. John Krasny
National Bureau of Standards
Room A363, Building 224
Route 270 and Quince Orchard Road
Gaithersburg
Maryland 20899

Dear John:

About a month ago, we received from you samples of nine experimental cigarettes which were manufactured as part of the the Second Series in the Technical Study Group's effort to examine the role played by the different components of cigarettes in affecting their ignition of soft furnishings. Kimberly-Clark was contracted to determine the permeability of the different plies of papers which wrap these cigarettes. This work was performed under your Department of Commerce Reference Number: 41 USC 252 C03 and your Order Number: 43NANB705681. We have completed the analyses and the data are presented in the table attached to this letter.

As with the work for which we were contracted last Fall, we measured the permeability of the papers using CORESTA Recommended Method No. 3 [Determination of the air permeability of cigarette paper, CORESTA Information Bulletin, 1975 (3,4)]. The data are reported as the velocity of air (in centimeters per minute) drawn through the paper at a pressure differential of one centibar (ten centimeters of water).

The sampling scheme used was as follows: five cigarettes were selected at random from each set and the wrapper(s) were removed. When an inner wrapper was present (Items 6-2, 7-2, 8-2 and 9-2), its permeability was determined at two different locations on each swatch for a total of ten readings. For the outer wrappers, five different positions were selected per swatch for a total of twenty-five measurements; in one case, Item 5-2, ten positions were measured per swatch for a total of fifty measurements. The reason for the additional testing was that the embossed samples gave such scattered readings, we wanted the mean to be as well-specified as possible.

Some other comments on the data are appropriate. For the four samples which were embossed--Items 4-2, 5-2, 8-2, anad 9-2--it is clear from an examination of the means and standard deviations (the latter range from twenty-five to seventy percent of the former) that the permeability of those papers have been increased non-reproducibly through the embossing process. This finding is merely a measured confirmation of what is readily apparent when one looks closely at those cigarettes. The embossing does not impinge on the measured permeability of the inner wrappers, where present, since those papers are so open that the embossing adds little or nothing to the net flow of air through them.

Item 1-2 was smaller in circumference (twenty-one millimeters vs. twenty-five millimeters) than were the other eight items. Items 3-2, 5-2, 7-2 and 9-2 were wrapped with a cigarette paper that has been electrically perforated.

Our invoice has been mailed to you under separate cover.

Best regards.

Sincerely,

Charles F. Mattina

cc: Dr. Richard G. Gann
Chairman, Technical Study Group
National Bureau of Standards
Gaithersburg, Maryland 20899

CFM:87008

Table 2-D-2. Paper Permeability of Series 2 Experimental Cigarettes Determined by Kimberly-Clark

| | OUTER WRAPPER | | | INNER WRAPPER | | | |
|---|---|---|---|---|---|---|---|
| Item No. | Permeability (cm/min) | Standard Deviation (cm/min) | N | Permeability (cm/min) | Standard Deviation (cm/min) | N | Embossed |
| 1-2 | 5.2 | 0.6 | 25 | -- | -- | -- | no |
| 2-2 | 6.4 | 0.8 | 25 | -- | -- | -- | no |
| 3-2 | 58 | 5.3 | 25 | -- | -- | -- | no |
| 4-2 | 87 | 59 | 25 | -- | -- | -- | yes |
| 5-2 | 160 | 49 | 50 | -- | -- | -- | yes |
| 6-2 | 6.2 | 1.2 | 25 | 7300 | 700 | 10 | no |
| 7-2 | 59 | 12 | 25 | 7700 | 700 | 10 | no |
| 8-2 | 84 | 47 | 25 | 6800 | 400 | 10 | yes |
| 9-2 | 140 | 33 | 25 | 7200 | 600 | 10 | yes |

# Appendix 2-E

| MEMO RECORD | AVOID ERRORS PUT IT IN WRITING | DATE March 23, 1987 |
|---|---|---|
| [redacted] TO: K.C. Gupta, DVM, Ph.D., HSHL | | OFFICE |
| [redacted] From: Saura Sahu, HSHL | | DIVISION |

SUBJECT: Citrate analysis in cigarette paper

SUMMARY

Introduction

The following 6 batches of cigarette papers were received for citrate analysis: Series 1-6, 1-7, 1-15, 1-18, 1-25 and 1-30.

Experimental Methods

The papers to be analized were weighed, cut into smaller pieces and extracted with distilled water. The paper extracts were centrifuged at 300 x g for 10 min to remove debris. The clear supernatants were analized for citrate.

The spectrophotometic method of Surles (Microchemical Journal 19, 153, 1974) was used for citrate analysis. A standard curve with known concentrations of sodium citrate was made to calculate the citrate concentration in the paper extracts. Briefly, the paper extract was taken in a 10 ml volumetric flask followed by 1 ml of ferric ammonium sulfate (2.5 g/l). The flasks were made up with distilled water and the absorbance of the resulting solution was measured at 375 nm. The absorbance of the solution before the addition of the $Fe^{+3}$ was subtracted from the absorbance of the solution after the addition of $Fe^{+3}$ to calculate the absorbance due to citrate.

Results

The weight of the paper extracted for analysis is given in Table 1. The standard curve of sodium citrate is given in Table 2 and Fig. 1. Table 3 and Fig. 2 give the absorbance of paper extracts without $Fe^{+3}$. Table 4 and Fig3 give absorbance of paper extract with $Fe^{+3}$. Table 5 gives absorbance due to citrate alone in the paper extract and the citrate concentration in the extract.

| SIGNATURE | DOCUMENT NUMBER |
|---|---|

CPSC Form 247 (4/76)

| MEMO RECORD | *AVOID ERRORS PUT IT IN WRITING* | DATE |
|---|---|---|
| FROM: | | OFFICE |
| TO: | | DIVISION |

SUBJECT

SUMMARY

Table 6 gives the citrate concentration in the 10 ml of total extract and its concentration in the cigarette paper by weight per cent.

Summary of Results

The citrate concentration, as determined spectrophotometrically with sodium citrate as the standard, was found in the cigarette paper in the following concentrations:

| Paper series | Citrate concentration (% by weight) |
|---|---|
| 1-6 | 0 |
| 1-7 | 0.74 |
| 1-15 | 0.57 |
| 1-18 | 0 |
| 1-25 | 0.61 |
| 1-30 | 0 |

| SIGNATURE | DOCUMENT NUMBER |
|---|---|
| | |

CPSC Form 247 (4/76)

# Appendix 2-F

June 17, 1986

Richard G. Gann, Chief
Fire Measurement & Research Division
Center for Fire Research
United States Dept. of Commerce
National Bureau of Standards
Gaithersburg, Maryland 20899

Dear Richard:

Enclosed are the data for the cigarettes you sent for us to analyze. Groups 1 through 8 and 17 through 24 are beyond a doubt burley cigarettes. This determination was made because of the low reducing sugar. I think there were some casing added prior to cigarette manufacturing; normally that is more closely related to sucrose but the extraction process is made with acid; therefore, some inversion to reducing sugars occurred. The remaining samples appear to be a blend of tobaccos. The reducing sugars are much too low for pure bright tobacco. Flue-cured cigarettes would be at least 15% or more reducing sugar. My guess; they are a blend 90:10 flue-cured + burley. One could determine nitrates quantitatively and total N and possibly positively confirm the composition. I discussed the analyses with a couple other experienced tobacco people and they confirm this hypothesis.

I hope this is some help. The data are included.

Sincerely,

Wes Weeks

Wes Weeks

/ds

Enclosure

# Appendix 2-G

UNITED STATES GOVERNMENT

## Memorandum

U S CONSUMER PRODUCT SAFETY COMMISSION

TO: John F. Krasny, Ph.D., Center for Fire Research
National Bureau of Standards

Through: Andrew G. Ulsamer, Ph.D., AED, HS AGU
Warren K. Porter, Director, HSHL WKP

FROM: Kailash C. Gupta, D.V.M., Ph.D., HSHL K Gupta

SUBJECT: Analysis for Na, K, Ca, and Mg Content in Fabrics and Cotton-Batting Specimens Provided by Dr. Krasny

The smoldering property of the cellulosic materials has been reported to be affected by the presence of inorganic free radical ions. The factors influencing the smoldering property of cellulosics are of interest to the Commission because of their impact on the fires resulting from cigarettes. Samples of five fabrics and three cotton battings provided by Dr. Krasny, of the National Bureau of Standards, were analyzed for Na, K, Ca, and Mg content. The results are provided in the attached table. Analysis of this data, along with data from other studies, will be conducted by Dr. Krasny.

The analytical procedures used were as follows:

Reference standard solutions (1000 ppm) for Na, K, Ca, and Mg, and the concentrated nitric acid were obtained from Fisher Scientific Company. Plastic laboratory wares were used as much as possible. The glassware, when used, was washed with a 35% nitric acid wash. The samples were shredded into small pieces and each subsample was analyzed in replicate. About a gram of material was digested with 50 ml of concentrated nitric acid by heating for 4 to 6 hours until it was completely digested and the solution was clear. Upon cooling, the digested solution was diluted with deionized distilled water to the appropriate dilutions. The standard solutions for each element and the reagent blanks were treated the same as the samples and run with each batch of samples. The elements were analyzed with a Leeman's Plasma Spec. I, ICP Spectrometer. A standard curve for each element was prepared for each batch of analysis. The elemental content of the materials was calculated using the standard curves, dilution factors, and the weight of material used. Reagent blanks were used for zero correction for sample analyte determination.

Attachment



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Table 2-G-1. Elemental Analysis of Upholstery Fabrics and Cotton Batting Determined by U.S. CPSC

Cotton Batting and Fabric
Elemental Analysis (PPM)*

| Material | Sub | Na | K | Ca | Mg |
|---|---|---|---|---|---|
| Cotton Batting | 1A | 216 ± 71 | 4650 ± 759 | 950 ± 26 | 423 ± 90 |
| 593-0180 | 1B | 210 ± 61 | 5082 ± 794 | 941 ± 63 | 493 ± 75 |
| 593-0181 | 2A | 229 ± 74 | 5073 ± 807 | 907 ± 42 | 507 ± 95 |
| | 2B | 214 ± 52 | 5418 ± 786 | 932 ± 45 | 579 ± 45 |
| 593-0182 | 3A | 268 ± 82 | 5236 ± 655 | 950 ± 22 | 560 ± 64 |
| | 3B | 221 ± 73 | 4952 ± 917 | 832 ± 76 | 507 ± 34 |
| Fabric | A | 681 ± 104 | <100 | 284 ± 36 | 89 ± 11 |
| 593-0175 | B | 633 ± 78 | <100 | 273 ± 60 | 98 ± 3 |
| | C | 671 ± 93 | <100 | 298 ± 36 | 95 ± 2 |
| Fabric | A | 599 ± 60 | 4796 ± 739 | 750 ± 67 | 541 ± 41 |
| 593-0176 | B | 484 ± 33 | 4596 ± 751 | 757 ± 95 | 568 ± 28 |
| | C | 683 ± 40 | 5279 ± 1147 | 759 ± 96 | 537 ± 33 |
| Fabric | A | 802 ± 97 | 5573 ± 688 | 30574 ± 4084 | 2938 ± 144 |
| 593-0177 | B | 790 ± 165 | 6599 ± 1285 | 27334 ± 1958 | 2672 ± 185 |
| | C | 851 ± 146 | 6236 ± 863 | 28998 ± 2080 | 3018 ± 245 |
| Fabric | A | 969 ± 55 | 391 ± 103 | 593 ± 70 | 411 ± 42 |
| 593-0178 | B | 1138 ± 113 | 449 ± 94 | 710 ± 73 | 468 ± 54 |
| | C | 992 ± 45 | 367 ± 82 | 547 ± 80 | 388 ± 76 |
| Fabric | A | 163 ± 36 | <100 | 554 ± 57 | 171 ± 21 |
| 593-0179 | B | 115 ± 34 | <100 | 466 ± 35 | 135 ± 10 |
| | C | 126 ± 42 | <100 | 463 ± 42 | 132 ± 10 |

*Results from five replicate analysis.

The Effect of
Cigarette Characteristics
on the Ignition
of Soft Furnishings

# Section 3

## Performance Measurements

## Contents for Section 3



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## Appendices

# Introduction

This section covers the evaluation of the ignition propensities of the previously described 41 experimental and five patented cigarettes under a variety of experimental conditions.[1] The results were compared with those obtained on current commercial cigarettes to determine performance relative to today's market. The procedure was to give all cigarettes a "primary evaluation," and then to confirm the results on selected cigarettes by exposing them to a wider variety of conditions simulating those which could occur when cigarettes are dropped inadvertently on upholstered furniture.

The primary evaluation consisted of placing each of the cigarettes on three mini-mockup substrates varying in cigarette ignition resistance. On one of these substrates, full-length as well as half-length cigarettes (to simulate cigarettes after they have been smoked for some time) were tested.

The main objective of the validation phase of this work was to assure that the relative ignition propensity rankings established in the primary evaluation hold true under the full range of substrate conditions under which cigarettes are dropped on upholstered furniture. Several low ignition propensity cigarettes were chosen for this purpose (since the emphasis in this work is on low ignition propensity) as well as intermediate propensity cigarettes and commercial controls. A variety of test conditions was used for this work, as follows:

To cover an as complete range of substrate cigarette ignition resistance as possible, experiments were carried out on over 20 substrates. These included a very low cigarette ignition resistant substrate, a heavy, raw cotton fabric and cotton batting or polyurethane foam padding.

To establish the effects of filters and of short tobacco columns, selected experimental cigarettes were evaluated with the filter and/or one half of the tobacco column removed.

The effect of cover fabric contamination on the relative ignition propensity of cigarettes was investigated. One of the contaminants used was alkali metal ions (known smolder-promoters) [3-1,2]. They were applied to a cotton duck fabric which, without treatment, did not ignite from any cigarette. Since furniture becomes soiled with use, tests were also conducted with soiled fabric from discarded furniture, and with the same fabrics after cleaning. Soil was also extracted from discarded furniture fabric covers and applied to the cotton duck fabric.

All the above work, as well as the primary evaluation, was carried out with mockup bench-scale tests. To evaluate the relevance of these bench-scale ignition propensity results, results obtained on 44 full-scale chairs (representing four flat and 19 crevice substrates) were compared with results on mockups containing the same materials in the same configurations.

It must be emphasized that these various modes of validation can only produce a ranking of the cigarettes which can be compared with the results of the primary evaluation. The actual number of ignitions in each of those modes depends on the cigarette ignition resistance of the substrate; one should thus not expect the same number of ignitions in the primary evaluation as in the validation tests.

The bench-scale evaluations will be described first, followed by a section on the comparison of the full-scale and bench-scale results and a short discussion of the smoke yields of the experimental cigarettes. Finally, the evaluation of patented cigarettes will be discussed.

[1](a) *Ignition is defined as sustained, expanding smoldering of the material on which the burning cigarette rests. This may or may not lead to flaming ignition.*

(b) *The term "substrate" is used to describe one combination of a specific fabric and padding, in either the flat or the crevice (juncture of vertical and horizontal cushions) configuration, with or without a sheet covering the cigarette. An example is the flat area of a piece of polyurethane foam covered with a specific fabric, with the cigarette covered by a piece of sheeting. The crevice made from the same materials is a different substrate.*

(c) *In this report, the term "cigarette ignition resistance" will be used to characterize substrates, with low cigarette ignition resistance used to describe substrates which ignite easily.*

(d) *Similarly, the term "ignition propensity" will be used to characterize cigarettes, with low ignition propensity cigarettes denoting those which are unlikely to ignite most substrates.*

# Bench-Scale Evaluations

## Methods

### Ignition Propensity Measurements

In both the primary evaluation and the validation measurements, the determination of the ignition propensity of the experimental and patented cigarettes was done in the same manner and using the same mockups and associated equipment as reported in Appendix B of [3-3]. Four minor changes were made for this study. The first change was the use of five (5) replicates per cigarette (unless otherwise indicated) for increased statistical precision. The second change was to use the same size vertical pad as horizontal pad (203 × 127 × 51 mm, 8 × 5 × 2 in.) in the crevice configuration, to save material and effort. The third change was to record as a smoldering ignition a weight loss of greater than 3.5 g (instead of 5.5 g) for polyurethane mockups in the flat configuration because the substrates had obviously ignited at this weight loss, and carrying the tests further would result in contamination of the ambient air. The fourth change was equilibrating the cigarettes (stored in freezers at −15°C) as well as the substrates, in a conditioned room at 55 ± 10% RH and 22 ± 3°C for a minimum of 24 hours. They were exposed to the less controlled conditions (20-60% RH, 23-26°C) in the test room for a maximum of 20 minutes before the last of the five tests were begun.

### Contamination of Fabrics with Alkali Metal Ions and Natural Soil

This work was part of the effort to confirm results of the primary evaluation under different test conditions as well as to investigate the effect of fabric contamination in a systematic manner. Only preliminary work was performed. Specifically, the objective was to determine whether cigarettes which had been found to have low ignition propensity in the preliminary evaluation would still maintain their low ignition propensity under conditions in which the fabric ignition resistance was changed by contamination. Two types of contamination were considered: (1) by alkali metal ions, which occurs in real life both on raw cotton and as a residue of a variety of fabric finishing agents and which are known smolder-promoters [3-1,2]; and (2) by soil recovered from discarded furniture cover fabrics.

The procedure for determining the effect of alkali metal ion concentration on the cigarette ignition resistance of fabrics in a systematic manner was as follows. It was established that a mockup of a 100% cotton duck fabric and polyurethane foam in the flat configuration was not ignited by a commercial cigarette, No. 6; this cigarette had been found to have an ignition propensity similar to that of several other commercial cigarettes in earlier work, with an ignition propensity typical of present production.[3-3] Various concentrations of $Na^+$, $K^+$, and $Na^+$ plus $K^+$ were then applied to the fabric until a concentration at which the ignition-prone cigarette would ignite the substrate was found. Then somewhat higher concentrations would be applied. Selected experimental cigarettes were then tested on these substrates, to establish whether their ignition propensities would still rank them as they had ranked in the primary evaluation.

For the treatment, the cotton duck fabric samples were immersed in solutions containing various concentrations of NaCl, KCl, or NaCl plus KCl and a wetting agent, then padded (immersion in the solution and extraction on "pad" rolls) and air dried in the horizontal attitude to prevent migration of the solutions over the fabric. (The work was conducted at the College of Human Ecology, The University of Maryland, College Park, Maryland). The approximate ion concentration on the fabric specimens was calculated from the wet pick-up of the specimens after padding them through the bath of known salt concentration; e.g., a specimen with a 60 percent wet pickup and a bath concentration of 8000 ppm would contain approximately 4800 ppm ions. Weighing the conditioned specimens before and after treatment would not provide accurate ion concentration results because the hygroscopicity of the specimens is undoubtedly changed by the added ions, and because the expected weight changes due to treatment are so small (add-ons in the range of 5 percent) that this uncertainty would matter. Also, yarns from the edges of specimens are often lost during treatment, and this further adds to the uncertainty of dry add-on determinations.

After the concentration for each ion and ion combination had been established, ten (10) 420 × 205 mm swatches of fabric containing the various ions and a control containing only the wetting agent were prepared. The test fabrics were evaluated over polyurethane foam or cotton batting in the flat configuration using the low ignition prone (BELN-21, No. 106) and a moderately ignition prone (FELC-25, No.129) cigarette of the Series 1 experimental cigarettes and the above commercial cigarette, No. 6.

Fourteen different soiled, discarded upholstery cover fabrics were collected from reupholstery establishments. Swatches of each fabric were retained. The remainder of the fabric was sent to The International Fabricare Institute, Silver Spring, Maryland. The soil was extracted by immersion in tetrachloroethylene and subsequently in water (without a wetting agent) and collected. The fabrics were returned to CFR for evaluation of cigarette ignition resistance and the soil was given to the Department of Human Ecology, University of Maryland, for application to the cotton duck. The soil extract which was still suspended in the solvent was not padded on but the duck specimens were immersed in the solutions, then air-dried horizontally. In one case the specimens were immersed first in the water, in the other case, first in the tetrachloroethylene. The specimens were dried and then immersed in the other solution. The solids add-on was about 3 percent in both cases. Time did not permit refining the method of application of the actual soil or choosing various concentration levels, nor analyzing the soil.

Specimens of the 14 soiled and extracted fabrics, of the purposely soiled cotton duck and a control which had been immersed in the two solvents were tested with three replicates each of the low ignition propensity experimental cigarette BELN-21, No. 106, and the commercial cigarette, No. 6.

## Results and Discussion

### Ignition Propensity Results

In this section, the results of the ignition propensity evaluations are described. In summary, in the primary evaluation, five of the 41 experimental cigarettes produced only 0 to 4 ignitions while typical commercial cigarettes produced 18 to 20 ignitions. (20 is the maximum possible number.) Thirteen of the experimental cigarettes produced 10 or fewer ignitions. The cigarettes which produced the low number of ignitions combined low packing density (attained by use of expanded, relatively large particle size tobacco), low paper permeability and paper citrate content, and small cigarette circumference. They contained Burley or flue-cured tobacco. During the validation process, the low ignition propensities of several cigarettes were further confirmed on additional substrates and under a variety of experimental conditions, in bench-scale tests as well as on full-scale chairs. It thus appears that some cigarettes which have significantly lower ignition propensity than current commercial cigarettes could be produced on commercial equipment without major hardware changes, albeit at reduced speed.

### Primary Evaluation of Experimental Cigarettes for Ignition Propensity

The number of ignitions of both series of experimental cigarettes are shown in Tables 3-1 (Series 1) and 3-2 (Series 2). Table 3-2 also shows comparable values for commercial cigarettes. Three substrates each representing a different level of cigarette ignition resistance of residential furniture were used; on one of these, both full length and half length cigarettes were exposed. These substrates ignited with all five replicates of the commercial cigarette, No. 6 [3-3]. All five replicates of another commercial, No. 3, ignited in three of the test modes; on one relatively high cigarette ignition resistance substrate, this cigarette caused ignition in 3 of 5 cases.

The first substrate listed in the tables, the standard California velvet over cotton batting in the flat configuration, had been previously used for the screening of commercial cigarettes [3-3]. The next substrate, a relatively heavy cotton fabric ("Splendor") over polyurethane foam, had a similar, low cigarette ignition resistance. Again, only cigarettes with low ignition propensity produced fewer than five ignitions. Finally, lower numbers of ignitions were obtained in the crevice configuration formed by a denim fabric over polyurethane foam, with the cigarette covered with a piece of sheeting. (The use of sheeting as a cover is prescribed in many procedures for testing the cigarette ignition resistance of upholstered furniture and mattresses [e.g., 3-4,5].) Evaluation of the results could then proceed by the total number of ignitions in the four test modes, e.g., 20 ignitions will be called high ignition propensity; this occurred with five of the 41 tested cigarettes. Four or fewer ignitions will be called low ignition propensity cigarettes; this occurred with five of the cigarettes.

The shortened cigarettes of Series 1 produced significantly lower number of ignitions (at the 0.2 percent significance level for the Series 1 cigarettes).

This was not observed for the cigarettes of the second series. The analysis of variance methods used are described in [3-6,7]. Additional results with shortened cigarettes on a different substrate are discussed below.

The average effects of the various cigarette design parameters of the Series 1 experimental cigarettes are shown in Table 3-3. (It should be noted that these are averages for 16 cigarettes with one parameter held constant and four other parameters systematically varied.) The data were analyzed by analysis of variance for a $2^5$ factorial design for each of the four ignition modes. The response variable was obtained by applying the Freeman-Tukey modification of the angular transformation to the raw count data shown in Table 3-3 [3-6,7,8]. Only overall effects are discussed here; more detailed statistical discussions are given in Appendix 3-A. The findings can be summarized as follows:

- Low packing density, achieved by use of expanded, large particle size tobacco (30 cut width) was the most

## Table 3-1. Ignition Propensity of Series 1 Experimental Cigarettes

| Cigarette No. | Design. | Number of Ignitions: CA/CB unc./flat | SPL/PU unc./flat | SPL/PU[a] unc./flat | Denim/PU crev./cov. | Total |
|---|---|---|---|---|---|---|
| 101 | BNLC-21 | 3 | 5 | 5 | 0 | 13 |
| 102 | BNLN-21 | 2 | 5 | 5 | 0 | 12 |
| 103 | BNHC-21 | 5 | 5 | 5 | 2 | 17 |
| 104 | BNHN-21 | 5 | 5 | 5 | 4 | 19 |
| 105 | BELC-21 | 0 | 3 | 3 | 0 | 6 |
| 106 | BELN-21 | 0 | 1 | 0 | 0 | 1 |
| 107 | BEHC-21 | 4 | 5 | 2 | 0 | 11 |
| 108 | BEHN-21 | 3 | 4 | 0 | 0 | 7 |
| 109 | FNLC-21 | 5 | 5 | 5 | 0 | 15 |
| 110 | FNLN-21 | 5 | 5 | 5 | 1 | 16 |
| 111 | FNHC-21 | 5 | 5 | 5 | 4 | 19 |
| 112 | FNHN-21 | 5 | 5 | 5 | 5 | 20 |
| 113 | FELC-21 | 0 | 5 | 1 | 0 | 6 |
| 114 | FELN-21 | 1 | 3 | 0 | 0 | 4 |
| 115 | FEHC-21 | 4 | 5 | 5 | 0 | 14 |
| 116 | FEHN-21 | 4 | 5 | 3 | 0 | 12 |
| 117 | BNLC-25 | 5 | 5 | 5 | 3 | 18 |
| 118 | BNLN-25 | 5 | 5 | 5 | 3 | 18 |
| 119 | BNHC-25 | 5 | 5 | 5 | 5 | 20 |
| 120 | BNHN-25 | 5 | 5 | 5 | 5 | 20 |
| 121 | BELC-25 | 5 | 5 | 4 | 0 | 14 |
| 122 | BELN-25 | 3 | 2 | 2 | 0 | 7 |
| 123 | BEHC-25 | 5 | 5 | 5 | 0 | 15 |
| 124 | BEHN-25 | 5 | 5 | 5 | 0 | 15 |
| 125 | FNLC-25 | 5 | 5 | 5 | 3 | 18 |
| 126 | FNLN-25 | 5 | 5 | 5 | 2 | 17 |
| 127 | FNHC-25 | 5 | 5 | 5 | 5 | 20 |
| 128 | FNHN-25 | 5 | 5 | 5 | 5 | 20 |
| 129 | FELC-25 | 5 | 3 | 2 | 0 | 10 |
| 130 | FELN-25 | 3 | 1 | 0 | 0 | 4 |
| 131 | FEHC-25 | 5 | 5 | 5 | 0 | 15 |
| 132 | FEHN-25 | 5 | 5 | 2 | 0 | 12 |
| | | 127 | 142 | 119 | 47 | 435 |

Maximum number of ignitions per cigarette is 20, per substrate 160.
CA/CB California test fabric/cotton batting
SPL/PU 100% cotton Splendor fabric/polyurethane 2045
Denim/PU 100% cotton Denim fabric/polyurethane 2045
Unc/flat Uncovered cigarette on a flat mockup
Crev/cov Covered cigarette in mockup crevice
[a] Cigarette with filter with one half of the tobacco column removed before lighting.

important factor in reducing ignition propensity. This effect was statistically significant at or below the 0.1 percent level for all test modes. This was apparently due to the reduction in the available fuel per unit length by 30 to 40 percent. Commercial cigarettes generally are a blend of non-expanded and expanded tobacco, with the latter component ranging between 10 and 65 percent [3-9]. The packing density of a popular, commercial, low tar-nicotine yield cigarette was found to be 0.18 mg/mm³, within manufacturing scatter of the packing density of one of the experimental cigarettes with the lowest ignition propensity, 0.17 mg/mm³.

- Second in importance was low paper permeability. This effect was significant at or below the 0.7 percent level for all test modes. The low permeability paper used in these experimental cigarettes, nominally 10 CORESTA, would probably rarely be used in commercial cigarettes, primarily because it could result in relatively high yields of tar, nicotine and CO. Papers with 20 to 70 CORESTA permeability, with a median range of 35 to 40, are used in commercial cigarettes [3-9]. However, other means are available to reduce these yields, such as improved filter design and use of the ventilation principle—holes near the filter which permit air to enter during the draw and dilute the smoke—are available [3-10]. Such ventilation reduces smoke yields as measured by the FTC method. However, the FTC does not measure the "side stream" smoke, the smoke which emanates from the cigarette between puffs.
- Cigarettes with 21 mm circumference were, as a group, less ignition prone than those with 25 mm circumference. This difference was significant at the 0.01 to 0.03 percent level for the California standard fabric/cotton batting and denim/polyurethane foam substrates, at the 3 percent level for the shortened cigarettes on the Splendor fabric/polyurethane substrate, and was not significant for the full length cigarettes on this substrate. (These results again indicate the dependency of ignition propensity results on the substrate.) Cigarettes with 21 mm circumference are

## Table 3-2. Ignition Propensity of Series 2 Experimental Cigarettes

| | Paper variables | | | | Mockup Test Conditions Number of Ignitions | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Permeability[a] CORESTA[b] | | | | | | | | |
| Cigarette number | Outer | Inner | Embossed | Circum. (mm) | CA/CB Unc./flat | SPL/PU Unc./flat | SPL/PI[c] Unc./flat | Denim/PU crev./cov. | Total ignitions |
| 201 | 5.2 | – | – | 21 | 0 | 0 | 0 | 0 | 0 |
| 202 | 6.4 | – | – | 25 | 2 | 0 | 0 | 0 | 2 |
| 203 | 58 | – | – | 25 | 4 | 1 | 2 | 0 | 7 |
| 204 | 87 | – | yes | 25 | 4 | 3 | 4 | 0 | 11 |
| 205 | 160 | – | yes | 25 | 5 | 3 | 3 | 0 | 11 |
| 206 | 6.2 | 7300 | – | 25 | 2 | 2 | 4 | 0 | 8 |
| 207 | 59 | 7700 | – | 25 | 1 | 3 | 3 | 0 | 7 |
| 208 | 84 | 6800 | yes | 25 | 5 | 5 | 4 | 0 | 14 |
| 209 | 140 | 7200 | yes | 25 | 3 | 5 | 5 | 0 | 13 |
| | | | | TOTALS | 26 | 22 | 25 | 0 | 73 |
| Commercial cigarettes | | | | | | | | | |
| 1 | lowest ignition propensity of 12 commercial cigarette packings | | | | 2 | 5 | 4 | 5 | 16 |
| 2 | | | | | 2 | 5 | 0 | 5 | 12 |
| 3 | ignition propensity typical of commercial cigarettes | | | | 5 | 5 | 5 | 3 | 18 |
| 6 | | | | | 5 | 5 | 5 | 5 | 20 |

(a) Measured at Kimberly Clark
(b) CORESTA corresponds to cm³/min·cm² at /cbar
(c) Cigarette with filter with one half of the tobacco column removed
CA/CB California test fabric/cotton batting
SPL/PU 100% cotton Splendor fabric/polyurethane 2045
Denim/PU 100% cotton Denim fabric/polyurethane 2045
Unc/flat Uncovered cigarette on a flat mockup
Crev/cov Covered cigarette in mockup crevice

B Burley
F Flue-cured
N 100% non-expanded tobacco
E 100% expanded tobacco

currently an article of commerce, and even cigarettes with about 17 mm circumference have been recently introduced. The lower ignition propensity of the 21 mm circumference cigarettes is probably due to both less available tobacco and paper per unit length and to reduced contact area with the substrate.

- Citrates are added to the cigarette paper to regulate the paper burn rate and to obtain ash of the desired coherence and appearance [3-11]. Overall, this had a highly variable effect on ignition propensity. The significance levels of this effect were 0.7 percent for shortened cigarettes on the Splendor fabric/polyurethane foam substrate, and 2 to 25 percent in the other modes. Overall statistical significance aside, it is noteworthy that the paper of the three lowest ignition propensity cigarettes in this series contained no citrate.
- The choice of Burley or flue-cured tobacco had no significant effect on the ignition propensity. Most commercial cigarettes contain a blend of these and other tobaccos. The data imply that this practice may not affect ignition propensity.

The experimental cigarettes of Series 2 were designed to probe the effect of paper permeability, paper embossing (hopefully providing less contact with the substrate), and the use of double layers of cigarette paper (Table 3-2). Paper permeability can be regulated by two methods: "inherent paper porosity" is adjusted by varying the amount of calcium carbonate in the slurry; further adjustments can be made by perforation of the paper by electrostatic, laser, or mechanical means [3-12]. It seemed of interest to establish whether the two methods to achieve a given level of permeability would have the same effect on ignition propensity; higher innate porosity has been reported to increase burn rate, while perforating the paper did not [3-13]. Consequently, a very low permeability (4-6 CORESTA) paper was chosen, and parts of this paper were electrostatically perforated and/or embossed.

The results shown in Table 3-2. indicate that the cigarettes 201 and 202, with the low permeability base paper, had very low ignition propensities. For the single layer paper cigarettes, ignition propensity increased at the higher permeabilities, whether due to perforating or embossing. The electrostatic perforation resulted in an increase to about 60 CORESTA, and a modest increase in ignitions. Embossing further increased the permeability and number of ignitions because holes were formed during the process. Adding a second layer of thin, highly permeable paper had no consistent effect.

The results again indicate that low paper permeability is one important route to reducing ignition propensity, as had been predicted by industry experts [3-14]. The embossing experiment was flawed because the permeability was inadvertently increased in this process. Use of a light weight, permeable inner wrapper does not seem to be promising.

### Validation of Ignition Propensity Primary Evaluation Results

In this section, results of ignition propensity tests performed under a much broader range of test conditions than in the primary evaluations are reported. The relative ignition propensity rankings obtained in the primary evaluation were confirmed, as described in detail below.

## Table 3-3. Ignition Propensity as a Function of Cigarette Parameters Series 1 Experimental Cigarettes

| Cigarette Parameters | Number of Ignitions[a] | % |
|---|---|---|
| Tobacco Packing Density | | |
| High | 282 | 88 |
| Low | 153 | 48 |
| Paper Permeability | | |
| High | 256 | 80 |
| Low | 179 | 56 |
| Cigarette Circumference (mm) | | |
| 25 | 243 | 76 |
| 21 | 192 | 60 |
| Paper Citrate Conc. (%) | | |
| 0.8 | 231 | 72 |
| 0 | 204 | 64 |
| Tobacco Blend | | |
| Flue-cured | 222 | 69 |
| Burley | 213 | 67 |

(a) Maximum possible number is 320 (16 packings × 4 substrates × 5 replicates)

**Ignition Propensity of Short Cigarettes and of Cigarettes with the Filter Removed.** It appears more likely that partially smoked cigarettes rather than full length cigarettes are dropped on upholstered furniture. The question arises whether evaluation of ignition propensity performed with full length cigarettes is valid for short cigarettes. Furthermore, it seemed of interest to determine whether the filter had an effect on cigarette ignition propensity.

In the primary evaluation, full length cigarettes and cigarettes with half of the tobacco column removed were tested on a substrate consisting of the Splendor fabric and polyurethane padding. Some of the shorter cigarettes had a somewhat lower ignition propensity so that, at least for this substrate, testing full length cigarettes provides a certain safety factor. However, similar experiments carried out on a second substrate, California fabric over cotton batting (Table 3-4), showed no difference between short and long cigarette ignition propensities. This held for normal cigarettes and cigarettes with the filter removed. The statistical methods used are discussed in [3-6,7]. (Similarly, there was no consistent effect of length among the patented cigarettes which will be discussed later.) The results indicate that length matters only on certain substrates, primarily those which take a long time to ignite.

On this substrate. removal of the filter significantly (at the 0.01 percent level) increased the ignition propensity, of full length cigarettes as well as of cigarettes with half of the tobacco column removed. This should not be interpreted to mean that all commercial non-filter cigarettes have higher ignition propensity since commercial filter and non-filter cigarettes generally also differ in other design factors. However, several investigators found a greater propensity to ignite of commercial non-filter cigarettes as compared to (not necessarily strictly comparable) filter cigarettes [3-15,16] while others have found no such difference, e.g.. [3-3]. A possible explanation is that the removal of the filter increases the overall oxygen supply to the smolder front. This is particularly noticeable at the very end of the cigarette, where increased glowing can be observed. In such cases, the increased burning may cause ignition of borderline substrates which resist ignition along the main part of the cigarette.

It should be mentioned that Canadian investigators found the opposite, an ignition propensity increase when one half and one third length cigarettes were placed into the depressions near the tufts of mattresses [3-17]. This can be ascribed to the fact that on very curved surfaces (near the tuft) the weight of the filter and the adjoining parts of the cigarettes may cause the burning end to be lifted from the surface, while it remains in contact with the surface when the cigarettes were short.

**Effect of Fabric Contamination on Ignition Propensity.** As described in more detail below, and based on a limited amount of experimental work, it appears that the cigarette rankings obtained in the primary evaluation were maintained on contaminated fabrics. Of the two contaminants investigated, alkali metal ions decreased substrate cigarette ignition resistance while soil collected on used furniture did not appear to have an effect. Time did not permit us to find the alkali metal concentrations which would show the differences between cigarettes in a quantitative manner, by number of ignitions and non-ignitions. However, the lower ignition propensity cigarettes produced considerably less char on these substrates than the high ignition propensity cigarettes. A methodology for systematic contamination of fabrics has been developed which, while in need of further development, may be useful in future studies.

The investigation of the effect of alkali metal ions was prompted by the finding that such ions decrease the cigarette ignition resistance of fabrics. This has been clearly demonstrated by work described in the literature [3-1,2]. In spite of the clear evidence of the importance of this factor, neither UFAC, the fabric finishers, nor the upholstered furniture manufacturers seem to have taken steps to reduce alkali metal ion concentration and thus to increase cigarette ignition resistance. Alkali metal ions are naturally found in raw cotton, such as unscoured fabrics and cotton batting.

In fabric finishing, they can be deposited in the fabrics by rinsing in hard water, by residual detergents, dye auxiliaries, softeners, or other finishing agents which contain such ions. They can be removed by scouring in soft water.

The primary evaluation work had been carried out on new fabrics containing only the incidental smolder-promoting contaminations found in raw cotton or those originating from the final fabric finishing steps. Two approaches were used in the present work which were intended to establish whether cigarette rankings obtained on new fabric would still be found on contaminated substrates. One was to apply alkali metal ions which are known smolder promoters to a scoured, undyed 100 percent cotton duck fabric which, in the untreated state, does not ignite. In addition, soil from 14 dirty fabrics which had been removed from furniture being prepared for re-upholstering was collected by extraction in

## Table 3-4. Ignition Propensity of Short Cigarettes and Cigarettes Without Filter

Substrate: CA standard fabric, cotton batting, flat, uncovered

| Cigarette number | | Number of Ignitions | | | |
|---|---|---|---|---|---|
| | | Cigarette with filter | 1/2 tobacco Cigarette w/o filter | 1/2 tobacco column with filter | 1/2 tobacco column w/o filter |
| 103 | BNHC-21 | 5 | 5 | 3 | 5 |
| 105 | BELC-21 | 0 | 5 | 0 | 5 |
| 106 | BELN-21 | 0 | 5 | 0 | 5 |
| 113 | FELC-21 | 0 | 4 | 0 | 5 |
| 114 | FELN-21 | 1 | 3 | 0 | 5 |
| 119 | BNHC-25 | 5 | 5 | 5 | 5 |
| 120 | BNHN-25 | 5 | 5 | 4 | 5 |
| | | 16 | 32 | 12 | 35 |

## Table 3-5. Ignition Behavior of Cigarettes on Alkali Metal Ion Treated Fabrics

Substrate: Cotton duck/polyurethane foam/flat

| Cigarette number | Ign mode[a] | Water control | NaCl | | KCl | | NaCl/KCl | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | Ratio 1:1 | Ratio 1:1.2 |
| | | 0 (ppm) | 5280 (ppm) | 5530 (ppm) | 4920 (ppm) | 5170 (ppm) | 5020 (ppm) | 5460 (ppm) |
| 106 (BELN-21) | SE | 1 | 2 | 2 | 4 | 2 | 3 | 3 |
| | NI | 4 | 3 | 3 | 1 | 3 | 2 | 2 |
| | I | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 129 (FELC-25) | SE | 2 | 1 | 0 | 3 | 1 | 4 | 0 |
| | NI | 3 | 4 | 5 | 2 | 4 | 1 | 5 |
| | I | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 (COM) | SE | 0 | 0 | 0 | 0 | 2 | 0 | 0 |
| | NI | 5 | 4 | 3 | 5 | 3 | 5 | 5 |
| | I | 0 | 1 | 2 | 0 | 0 | 0 | 0 |

(a) SE - Cigarette self-extinguished
NI - Cigarette burned whole length, substrate did not ignite
I - Substrate ignited

water and solvent and applied to the same fabric. Such fabric soil could, of course, contain smolder-promoting ions (such as sodium from perspiration, etc.). However, their effect could be diluted if the soil contained possible smolder inhibitors; mineral dust comes to mind. In a smaller, less controlled effort, high and low ignition propensity cigarettes were placed on substrates made up from the 14 soiled fabrics and cotton batting, and compared with the results after the fabrics were cleaned.

A study comparing new chairs with the same chairs after considerable use was undertaken at Cornell University [3-18]. A small decrease in cigarette ignition resistance due to use was reported. However, the criterion used, measurement of surface char length five or ten minutes after exposure of the cigarettes, would not be appropriate in light of more recent experience that surface smoldering rate is not a proper evaluation procedure for ignition propensity. This is because smoldering can proceed into the substrate without expansion on the surface so that one must rely on signs of obvious ignition such as considerable smoke and heat evolution [e.g., 3-19]. However, we have found that char damage caused by cigarettes after they burn their entire length but do not ignite the substrates is related to their ignition propensity as established on other substrates.

Effect of Alkali Metal Ions. Table 3-5 shows the behavior of five replicates each of three cigarettes placed on fabrics treated with two concentrations each of NaCl, KCl, and NaCl/KCl combined. The two concentrations were chosen on the basis of a limited amount of screening of specimens with a wider range of concentrations. They did not produce quantitative ignition/non-ignition results as had been hoped but provided qualitative information based on the char damage on non-igniting substrates. The cigarettes chosen were BELN-21, No. 106 representing low ignition propensity, FELC-25, No.129, representing intermediate ignition propensity and the commercial cigarette No. 6. The results are shown in terms of cigarettes which self-extinguished, of those which burned their entire length but did not ignite the substrates, and those which ignited the substrate.

The commercial cigarette ignited the substrates in only three of 35 tests. However, it burned its entire length without igniting the substrate in 30 tests, and self-extinguished before burning its entire length in only 2 tests.

On the other hand, cigarettes Nos. 106 and 129 did not cause any ignitions. More than half of the cigarette No. 106 replicates self-extinguished before burning their entire length, as did about a third of the cigarette No. 129 replicates. Again, the remaining cigarettes burned their entire length. Thus, the size of the char ranked the cigarettes in the same manner as the ignition/non-ignition results of the primary evaluation which had been performed on substrates with lower cigarette ignition resistance. Similarly, the substrate/cigarette system weight losses of non-igniting substrates were largest for the commercial cigarette No. 6, intermediate for No. 129, and lowest for No. 106. As discussed in the first report on cigarette ignition propensity, these weight losses occasionally vary considerably between replicates [3-3], and were therefore not treated statistically. But they showed, understandably, similar trends to the visually observed char pattern sizes on the fabrics. These char patterns, as on many borderline ignition/non-ignition substrates, showed Rohrschach-like forms.

Unfortunately, nothing quantitative can be said about the effect of various levels of alkali metal ion concentrations. The concentration levels shown in Table 3-5 are only approximate, as discussed earlier, and can be considered duplicate treatments. (The differences between the two levels shown was smaller than intended, but such are the vagaries of experimental treatments with no time for repeats.) However, with both the concentration and the cigarette behavior very similar, it appears that two similar treatments with three salts gave very similar ignition propensity results. This is of importance because fabrics treated to various levels of alkali metal concentrations may be candidates for standard materials for both upholstered furniture cigarette ignition resistance and cigarette ignition propensity testing.

Soiled Fabrics. In limited experiments, soiling during use of fabrics did not seem to have an effect on cigarette ignition resistance, nor did it have an effect on the relative ignition propensity ranking of cigarettes. The details follow.

The 14 soiled fabrics removed from used furniture and their cleaned and conditioned counterparts were found to have the same cigarette ignition resistance. More specifically, the commercial cigarette No. 6 ignited seven of the soiled fabrics and six of the same fabrics after extraction (only one replicate cigarette used). No ignition with either soiled or extracted fabric occurred with cigarettes Nos. 106 or 129.

Table 3-6 shows the results obtained on cotton duck fabrics treated with the combined soil extracted from other parts of the above 14 soiled fabrics. The white cotton duck appeared very discolored after these treatments; the concentration of the soil of about 3 percent can only be approximately stated, since soil was first deposited from one extraction bath – trichloroethylene or water – then from the other. (This order was reversed in a second treatment series.) Some soil deposited in the first treatment may have been removed by the second treatment. The results show that even at this apparently high soiling level, the cigarette ignition resistance of this substrate was not increased over that of the unsoiled fabric. The cigarette with the lowest ignition propensity, BELN-21, No. 106, self-extinguished more frequently before burning its entire length that the other two cigarettes. Again, the difference can be only stated qualitatively on the basis of frequency of self-extinguishment and non-ignition since no ignitions occurred.

**Validation of Low Ignition Propensity on Additional Substrates.** Table 3-7 shows that the relative ignition propensities of commercial and low ignition propensity, experimental cigarettes were maintained when they were tested on three additional substrates. "Haitian cotton" fabric was chosen because a large number of studies

## Table 3-6. Ignition Behavior of Cigarettes on Soiled Fabrics

Substrate: Cotton duck/polyurethane/flat

| Cigarette number | Ign. Mode[a] | Water/Perc. Control | Soiled Specimens: Perc./water[b] 3500 ppm[d] | Soiled Specimens: Water/Perc.[c] 3.48 ppm[d] |
|---|---|---|---|---|
| 106 BELN-21 | SE | 2 | 1 | 1 |
| | NI | 1 | 2 | 2 |
| | I | 0 | 0 | 0 |
| 129 FELC-25 | SE | 0 | 0 | 1 |
| | NI | 3 | 3 | 2 |
| | I | 0 | 0 | 0 |
| 6 COM | SE | 0 | 0 | 0 |
| | NI | 3 | 3 | 3 |
| | I | 0 | 0 | 0 |

(a) SE – Cigarette self-extinguished
NI – Cigarette burned whole length, substrate did not ignite
I – Substrate ignited
(b) Specimen first treated with perchloroethylene soil extract, then water extract.
(c) Specimen first treated with water extract, then perchloroethylene extract
(d) Concentrations shown are maximum possible values; some of deposit from first treatment may have been removed by second treatment.

## Table 3-7. Ignition Propensity of Selected Cigarettes on Low Cigarette Ignition Resistance Substrates

| | Number of Ignitions Haitian Cotton | | |
|---|---|---|---|
| | Polyurethane | Cotton batting | |
| Cigarette | Flat | Flat | Crevice |
| 106 (BELN-21) | 1 | 0 | 0 |
| 114 (FELN-21) | 1 | 0 | —[a] |
| 130 (FELN-25) | 2 | 1[b] | —[a] |
| 201 | 0 | 1[b] | —[a] |
| 202 | 0[b] | 0[b] | —[a] |
| Commercial Cigarettes | | | |
| 1 | 5 | 5 | —[a] |
| 2 | 5 | 5 | —[a] |
| 6 | 5 | 5 | 5 |

(a) Untested
(b) Some replicates self-extinguished on the substrate

(summarized in [3-20]) have shown that heavy cotton fabrics which contain high concentrations of alkali metal ions (see Table 2-9 and Appendix 2-7, Fabric 593-0177) have very low cigarette ignition resistance. (A chair made with a similar Haitian cotton/cotton batting combination and ignited with a commercial cigarette placed into the crevice smoldered so vigorously that it burst into flames in 22 minutes, the shortest such transition time on record [3-20,21].) It seemed of interest to test cigarettes which had shown low ignition propensity on other substrates (including those used in the full-scale tests discussed below) on such an approximately worst case fabric. (Cotton batting without fabric cover or covered by very light weight fabrics—which are not generally used in upholstered furniture or mattresses—may have an even lower cigarette ignition resistance than the Haitian cotton fabric covered substrates.) This fabric was used over cotton batting as well as polyurethane foam, the former in both the flat and crevice configurations. There were zero or only one ignition with the low ignition propensity cigarettes BELN-21, No. 106, FELN-21, No. 114, and Nos. 201 and 202. A cigarette with intermediate ignition propensity, FELN-25, No. 130, produced three ignitions.

Three commercial cigarettes were used for comparison. No. 6 had been found to have an ignition propensity which was typical of that of eight other commercial cigarettes; Nos. 1 and 2 had been found to have somewhat lower ignition propensity [3-3].

The full-scale and comparative bench-scale experiments described below further validated the ignition propensity rankings obtained in the primary evaluation.

# 1

# Comparison of Full-Scale Furniture and Bench-Scale Tests

## Objective

The objective of these full-scale tests is to assess the validity of the ignition data from the mini-mockup tests and thus determine whether the apparent low ignition propensities of some of the experimental cigarettes are true.

## Method

The furniture fabrics, padding, and welt cord were chosen by UFAC and the chairs were manufactured under their supervision. Some of the chosen materials would not meet UFAC standards. They represent various levels of cigarette ignition resistance. The substrates included cotton batting and polyurethane foam as padding, and four cotton fabrics and one olefin fabric (see Section 2). Four or six identical upholstered chairs were delivered at a time, and because of the short time for execution of the testing, were usually completely tested before the next delivery. A chosen set of cigarettes was used on the cushion, and in the crevices of the chair.

### Cigarette Selection, Handling and Coding

The test plan for this portion of the program was based on the use of five cigarette types, spanning the range of possible fire safety modifications of cigarette design. The types included a representative commercial design that was expected to ignite most of the fabric-padding combinations to be tested, three experimental cigarettes that probably would not ignite these combinations, and one "in-between" experimental cigarette. This selection was designed to provide a sensitive indicator of any differences in measuring ignition propensity between these full-scale tests and the bench-scale test method.

The cigarettes were stored in a conditioning room at 55 ± 10% relative humidity and 22 ± 3°C. Enough cigarettes for one series of tests (5 to 10 of each kind) were removed from the conditioning room, marked "A," "B," . . . "E" as appropriate on the paper seam near the butt, and taken to the burn room (relative humidity about 30%). They were used over the times required for that day's tests. The (arbitrary) cigarette designations used in the data book, in the data tables, and to mark sites were:

A. Commercial No. 6
B. Series 2, No. 201
C. Series 1, No. 129 (FELC-25)
D. Series 1, No. 114 (FELN-21)
E. Series 1, No. 106 (BELN-21)

All cigarettes had filters except Commercial No. 6.

### Experimental Design

A rigorous experimental design was prepared for these tests, but proved to be impractical.

The original design involved randomizing the order of the chairs and the placement of the different kinds of cigarettes, with several different cigarettes used simultaneously in each test. The reasons this design was impractical are:

(a) Some cigarettes, if they were going to ignite the chair, would do so long before the other cigarettes had burned to completion. Since we could not extinguish a single smolder zone without affecting the other cigarette tests, the first smolder zone would grow massively. There was always danger the massive zone would erupt into flaming, and in any event its smoke created a problem and the large smoldering zone was difficult to extinguish.

(b) The chairs were generally delivered in groups of 4 (identical) chairs, several days apart. Each group of 4 was usually completely tested before the next groups were available for test.

So each set of 4 chairs was fully tested as received, and with all the cigarettes the same in a given test of a given chair.

Chairs were tested with cigarettes on the cushions and, (in separate tests) in the crevices as discussed under "Test Procedure."

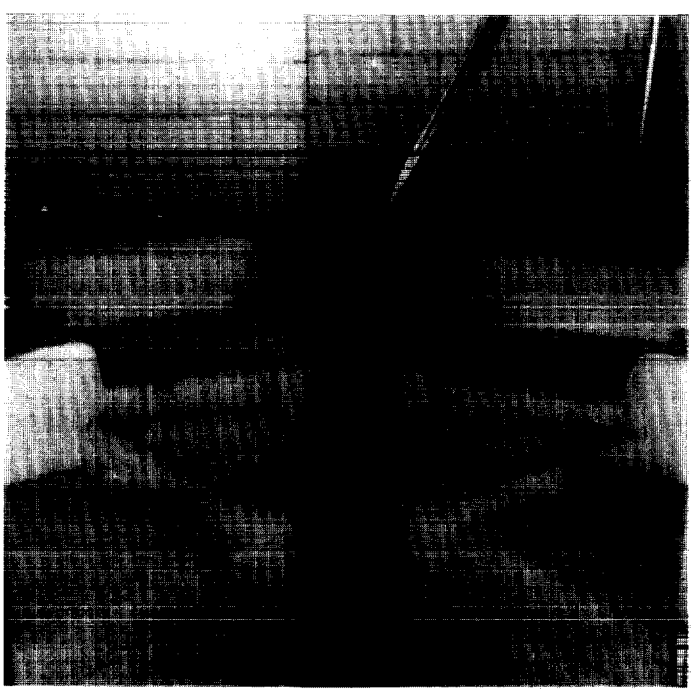
## Test Procedure for Full-Scale Furniture Tests

### General

As many as 4 chairs could be under test at any one time, each with multiple (up to 5) cigarettes on it. All 4 chairs could be viewed through the window in the burn room door, as shown in Figure 3-1, and any resulting smoldering could be extinguished by gaseous nitrogen injected into the smolder zone by a tube with small holes in the discharge end (Figure 3-2). A thin aluminum foil disk with a central hole for the nitrogen tube was used to "seal off" the smolder zone to prevent air being entrained into the zone. Since it was possible that nitrogen would flow through the padding to zones near other cigarettes, it was assumed that the use of nitrogen might have an effect on possible ignition by the other cigarettes on that chair. However, multiple identical cigarettes could be used on a single chair by delaying extinction until all had yielded test data.

As previously mentioned, the chairs in each group of four were identical. However, in most chairs the padding on the sides of the chair was different (cotton batting) from the padding on the back (polyurethane foam). In these cases the side crevice was considered a different test than the back crevice.

**Figure 3-1. Four Chairs as Viewed Through the Window of the Burn Room. Note that a Second Set of Cushions is in Place Permitting Additional Cigarette Tests in a Second Set of Crevices**



Some difficulties or differences encountered during the tests are described in a following section of this report.

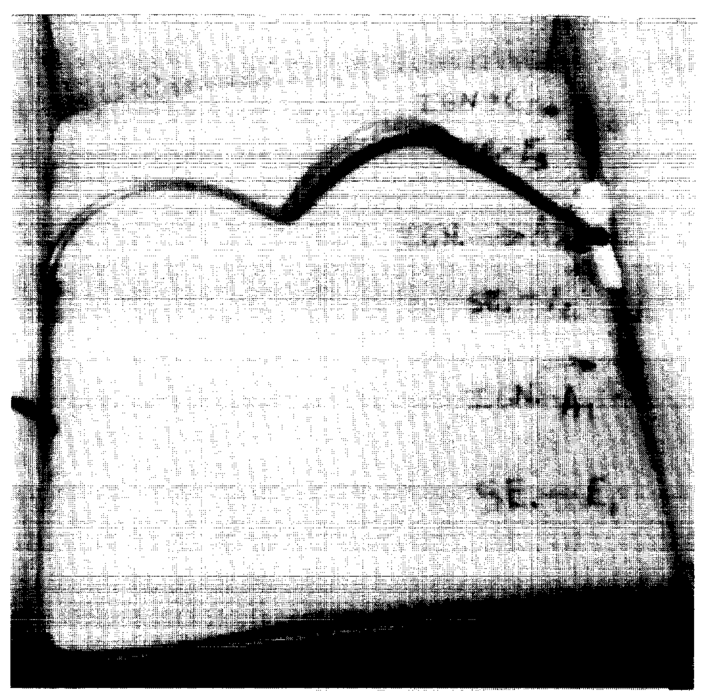
### Cigarette Location and Placement

The planned cigarette locations were randomized and marked on the cushions as shown in Figure 3-3 and Figure 3-4. Cigarettes were ignited, allowed to burn in air for 1 minute (this reduced the tendency for the cigarettes to self-extinguish on the chair) and placed near, not on, the mark.

Crevices caused a special problem in cigarette placement. Sometimes the cushions, as made, did not contact the sides or backs closely to form a "right angle" joint. We always adjusted the position and shape of the cushion, to the degree that was possible, to achieve a good joint, but sometimes an "acute angle" (wedge-shaped gap) was the best possible fit. When placing cigarettes in crevices next to welt cords, the cigarettes were located on the chair side of the welt cord (against the arm or back of the chair). This was done as a precaution since some of the welt cord was found to be smolder-resistant. A cigarette on the cushion side of the welt cord might ignite the cushion, but this would not constitute a crevice test. If the crevice was shaped so that the cigarette could only be placed on top of the welt cord (Figure 3-5), of course this was done. Also, in the case of an "acute angle" crevice, the cigarette might lie below the upper surface level of the cushion.

Extra cushions were requested and were provided so that an adequate number of crevice tests could be performed.

**Figure 3-2. Gaseous Nitrogen Applicator Used to Estinguish Ignited Sites**



After crevices next to the original cushion had been tested (leaving scorch marks), the extra cushion was placed on top of the original cushion, providing a second set of crevices against the arms and back of the chair, not near the previous scorch marks.

As previously mentioned, each cigarette was marked on the paper seam, near the butt, with its code letter. This insured that the right cigarette was used, and that contact with the fabric was not on the paper seam.

The several ignited cigarettes were placed on the chairs at 10 second intervals. This facilitated measuring the time to ignition, if ignition took place.

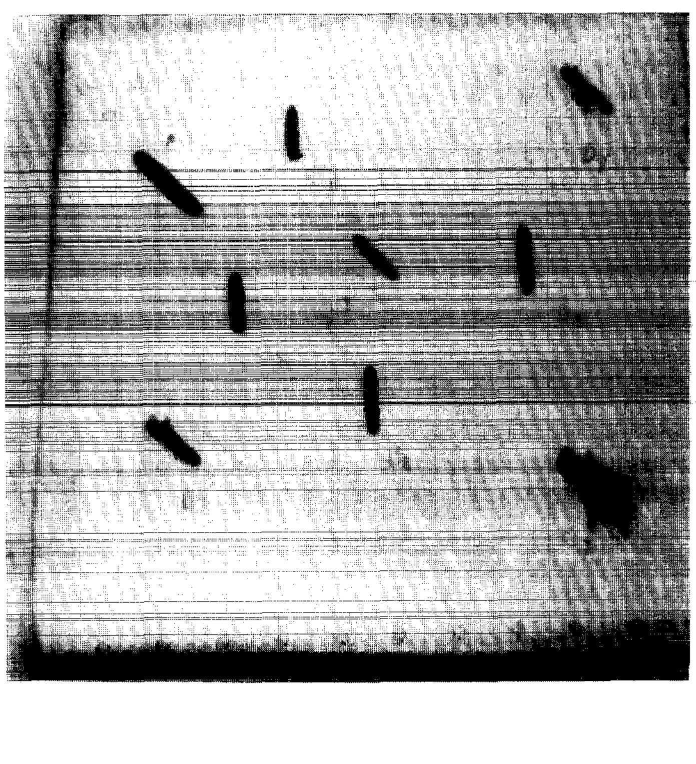
### Criteria for Ignition

The three criteria selected for an ignition were:

(a) Size of smolder zone — at least 1 inch from the side or end of the cigarette scorch mark on the upholstery. The padding must be involved. We experienced no self-extinguishments after the padding had been involved to this degree. The scorch mark at C7 in Figure 3-3, for instance, was not deemed an ignition because the foam padding was not involved. Instead, only the fabric smoldered, and then went out by itself.

(b) Amount of smoke — must be substantially more than that from the cigarette alone. For an example, see Figure 3-4, location A5.

**Figure 3-3. Sites for Various Cigarette Types Marked on a Damask Cushion, With Burn Scars Near the Marks.** There were no Ignitions in these Tests



(c) Color of smoke — yellowish if the polyurethane foam is involved. In most of the crevice tests the padding was cotton batting, so in those tests there was no yellow smoke.

Tests could be viewed through the window in the door to the burn room, or by a technician in the burn room who wore a mask attached to a cylinder of breathing air (smoke from the polyurethane foam is irritating). The room had an air-handling system which included a separate supply and exhaust, so no smoke leaked into the rest of the building.

If the cigarette self-extinguished before it fully burned, it was removed, and replaced by a new ignited cigarette of the same type near the same site. The summary tables of data are based primarily on results that would have been obtained if the cigarette had not been replaced, but the additional data are useful as a guide to the propensity of that cigarette design to ignite the fabric-padding configuration.

## Data from Full-Scale Tests

Locations of cigarettes, whether or not they ignited the substrate, and if they did, the time to obvious ignition were all recorded in the project data book, and into the attached

**Figure 3-4. Sites for Various "Crevice" Tests Marked on a "California Velvet" Cushion.** Site A5 is an Ignition — Note Smoke. Site AI was Ignited, then Extinguished in an Earlier Test

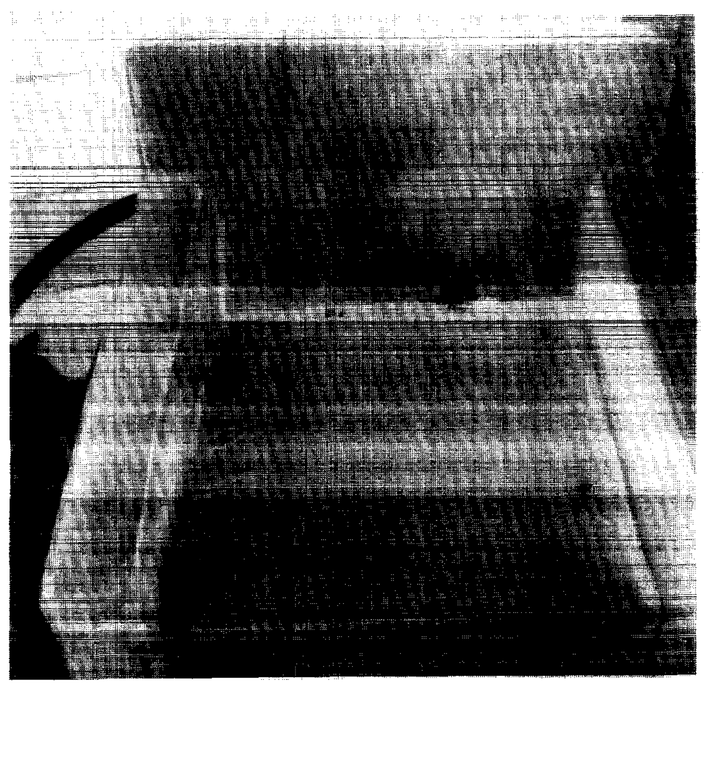
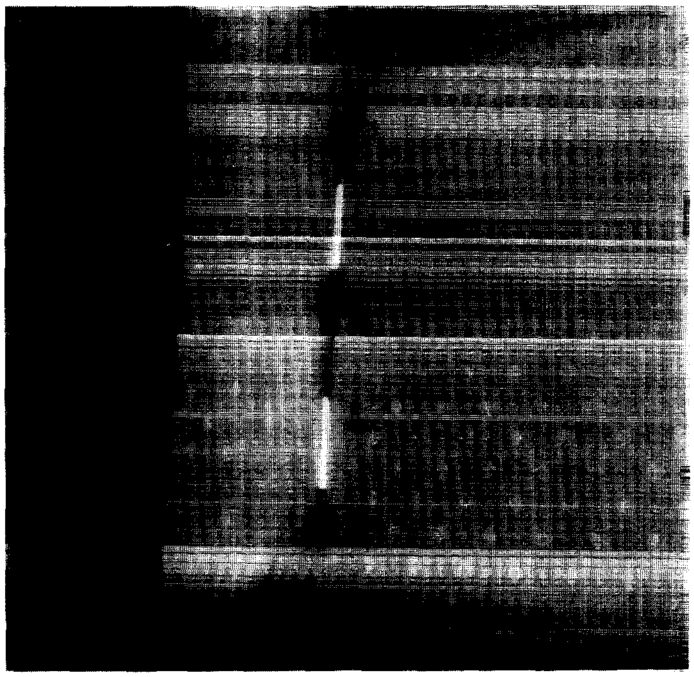


**Figure 3-5. Cigarettes on Top of Welt Cord When Cushion Shape Prevented Placement Beside Welt Cord**



summary tables (Tables 3-8A,B,C). In general there is one table for each chair type. Chairs with welt cords are considered a different type than similar chairs without welt cords, and are recorded in separate tables.

## Difficulties with the Procedure

Several contingencies are noted here that could potentially affect the accuracy of the results.

### Conditioning of the Chairs

The first chair tested was run within 2 hours after it had been delivered by truck from the manufacturer. Probably it had been exposed to higher relative humidities than the laboratory environment (about 30%). At any rate, it seemed to ignite slightly less readily than sister chairs stored in the laboratory one or more days. Subsequently all chairs were stored in the laboratory at 30% relative humidity for one or more days before testing.

### Drafts

In an early test (California velvet over cotton batting padding—see Figure 3-4) where considerable smoke was evolved, the door to the burn room was propped open about 6 inches. The resulting draft could be seen to blow the smoke around in a turbulent fashion. In the next test (a crevice test with the same substrate) all the cigarettes ignited the crevice, whereas in an earlier crevice test on this kind of chair, only the A cigarette had caused ignition. These latter data were discarded.

Later we measured the air velocities on the cushion under these conditions. They were:

- Normal ventilation—20-25 ft./minute (7-8 m/min.)—few gusts
- Door propped open—40-60 ft./minute, (13-20 m/min.) gusts to 80 ft./minute (26 m/min.)
- Bench-scale tests—average 14 ft./minute (5 m/min.)—few gusts
- Note: a 1 mph breeze is 88 ft./minute (29 m/min.)

Subsequent tests on later chairs (all with polyurethane padding) failed to show any effect of the drafts that occurred with the door propped open.

From time to time one of the test personnel would open the door briefly, pass through it, and close it while a test was proceeding. This did not cause drafts since the automatic control system, designed to keep the burn room at a slightly lower pressure than ambient, had a 15 second delay. It would not cause a large air flow through the door unless the door were held open for that length of time.

### Self-extinguishment of Cigarettes

Cigarettes that self-extinguished were replaced with new ignited cigarettes of the same type near the same site at least once to complete the test, but not before waiting about 10 minutes, to make sure that incipient smoldering had not occurred. In 63 of these cases, the second identical cigarette either ignited the substrate (25 cases) or burned without igniting the substrate (38 cases). In 553 cases the second cigarette also self-extinguished.

Usually self-extinguishment occurred soon after the cigarette was placed on the substrate, leaving only a minor scorch mark on it; but in some cases the cigarette burned longer before self-extinguishing. Therefore, we deemed it a "self-extinction" if the scorch mark was less than 1 inch long, and a "non-ignition" if longer than 1 inch.

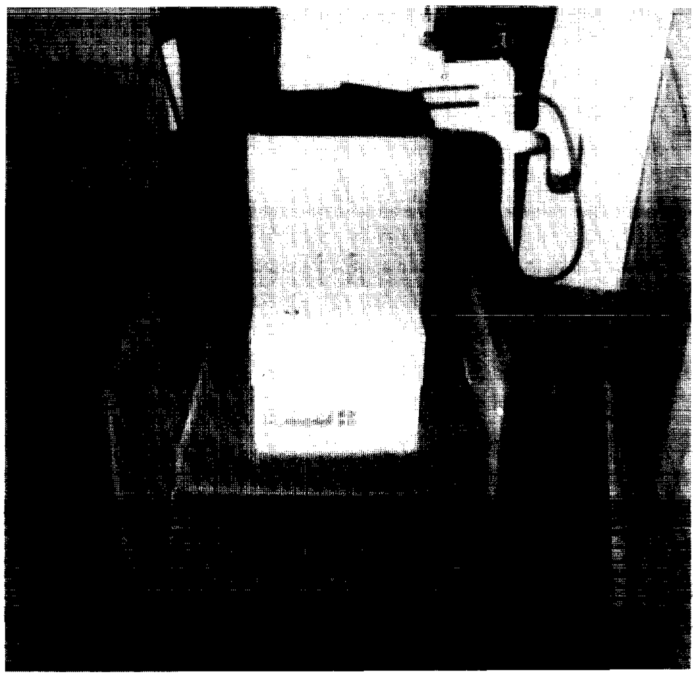
### Times to Ignition of Substrate

The times-to-ignition that were recorded are unavoidably inexact. There is some subjectivity to deciding when ignition of the substrate is certain. One would expect, therefore, that the times-to-ignition would be greater than those determined from weight loss traces in the bench-scale tests. This comparison of full-scale and bench-scale tests was not made because of the strong correlation of the ignition data. Further comparisons were considered redundant.

### Crevice Shape

Difficulties with obtaining a proper crevice shape have been described under "Cigarette Location and Placement." A few tests were carried out with weights on the cotton batting filled cushions (Figure 3-6) to cause "acute angle" crevices similar to those that would be caused by an occupant sitting in the chair. Foam cushions were so firm that this application of weights did not change the shape of the crevice.

## Figure 3-6. Weight on (Cotton Batting) Cushion Simulating Seated Person Causes "Acute Angle" Crevice Shape



### Influence of Substrate on Cigarette Burning

With heavy cotton velvet, two of the commercial cigarettes, No. 6, caused smoldering ignition of a welt cord crevice after the cigarettes smoldered for times of 58:45 and 61:00 minutes. The other identical cigarettes either did not ignite or self-extinguished before burning completely. Usually, if ignition were to happen it would occur in 20 minutes or less. Without the welt cord this unfiltered cigarette caused crevice ignition in 30-36 minutes. We have no explanations, only conjectures, for the long cigarette burn times. As for substrate ignition at the end of cigarette burning, it has been observed by others [3-16] that an unfiltered cigarette can ignite a substrate at the end of burning because the cigarette coal at that time gets ventilation from both sides, and can burn hotter.

## Results

### Validation of Bench-Scale Tests by Full-Scale Tests

Tables 3-8A, B and C list the percentage of ignitions for each cigarette type for each kind of chair construction and each location on the chair (cushion, crevice with welt and crevice without welt cord). These data are compared in the same tables with results of the bench-scale tests. It is concluded that the bench-scale tests are validated in 64 out of the maximum possible 75 cases.

The criterion for comparison is as follows:

> The full-scale results are based on 10 or more cigarettes, and the bench-scale on 5 cigarettes. The results are considered in agreement if the percentage ignition would be the same if one of the five bench-scale single cigarette tests had come out differently.

A further look at the results show that deviations from bench-scale to full-scale agreement were distributed as follows among the cigarette types:

| Type of Cigarette | No. of Agreement | No. of Non-agreement | Comments |
|---|---|---|---|
| A (6) | 14 | 1 | a commercial cig. No. 6 [3-3] |
| B (201) | 14 | 1 | low ign. propensity |
| C (129) | 11 | 4 | an "in between" cig. |
| D (114) | 12 | 3 | low ign. propensity |
| E (106) | 13 | 2 | low ign. propensity |
| Total | 64 | 11 | |

Thus those cigarettes with low ignition propensity (B, D, and E) and those with normal ignition propensity (A) gave results such that the full-scale tests and the bench-scale tests agreed in 53 out of 60 cases.

The conclusion is that the bench-scale tests can be used with a high degree of confidence to predict full-scale performance. This is in agreement with findings by the Consumer Product Safety Commission laboratories which tested full-scale, commercial chairs and then mockups made from the remaining materials [3-22]. The agreement between the tests was good in those cases when the same fabrics were used in both tests.

## Table 3-8A. Summary of Full-Scale Furniture Test Results
**(First cigarette per test only)**

| | | | | | | Bench-scale Comparisons | | |
|---|---|---|---|---|---|---|---|---|
| Material | Location | Cig. Type | Ignitions | Tests | % | Ignitions | No. of Tests | % Ignition |
| Calif | Cushion | A | 12 | 12 | 100 | 5 | 5 | 100 |
| velvet | | B | 9 | 12 | 75 | 0 | 5 | 0 |
| over | | C | 12 | 13 | 92 | 5 | 5 | 100 |
| cotton | | D | 10 | 12 | 83 | 2 | 5 | 40 |
| batting | | E | 5 | 12 | 42 | 1 | 5 | 20 |
| Calif | Crevice | A | 14 | 14 | 100 | 5 | 5 | 100 |
| velvet | (no welt | B | 4 | 24 | 17 | 0 | 5 | 0 |
| over | cord) | C | 12 | 14 | 86 | 0 | 5 | 0 |
| cotton | | D | 8 | 19 | 42 | 1 | 5 | 20 |
| batting | | E | 3 | 19 | 16 | 0 | 5 | 0 |
| Calif | Crevice | A | 10 | 10 | 100 | 5 | 5 | 100 |
| velvet | (with welt | B | 0 | 10 | 0 | 0 | 5 | 0 |
| over | cord) | C | 7 | 15 | 47 | 1 | 5 | 20 |
| cotton | | D | 2 | 17 | 12 | 1 | 5 | 20 |
| batting | | E | 0 | 14 | 0 | 1 | 5 | 20 |
| "Splendor" | Cushion | | | | | | | |
| (cotton) | | A | 10 | 10 | 100 | 5 | 5 | 100 |
| over P.U. | | B | 0 | 16 | 0 | 0 | 5 | 0 |
| Foam | | C | 10 | 10 | 100 | 2 | 5 | 40 |
| | | D | 8 | 11 | 73 | 1 | 5 | 20 |
| | | E | 3 | 10 | 30 | 0 | 5 | 0 |
| "Splendor" | Crevice | | | | | | | |
| (cotton) | (no welt | A | 10 | 10 | 100 | 5 | 5 | 100 |
| over P.U. | cord) | B | 0 | 20 | 0 | 0 | 5 | 0 |
| Foam | | C | 1 | 19 | 5 | 0 | 5 | 0 |
| | | D | 0 | 20 | 0 | 0 | 5 | 0 |
| | | E | 0 | 20 | 0 | 0 | 5 | 0 |
| "Splendor" | Crevice | | | | | | | |
| (cotton) | (with | A | 10 | 10 | 100 | 5 | 5 | 100 |
| over P.U. | welt | B | 0 | 20 | 0 | 0 | 5 | 0 |
| Foam | cord) | C | 0 | 20 | 0 | 0 | 5 | 0 |
| | | D | 0 | 20 | 0 | 0 | 5 | 0 |
| | | E | 0 | 20 | 0 | 0 | 5 | 0 |
| | | F[a] | | | | 4 | 4 | 100 |

(a) Commercial Series 3

**Table 3-8B. Summary of Full-Scale Furniture Test Results**
**(First cigarette per test only)**

| Material | Location | Cig. Type | Ignitions | Tests | % | Bench-scale Comparisons: Ignitions | No. of Tests | % Ignition |
|---|---|---|---|---|---|---|---|---|
| Damask over Foam | Cushion | A | 0 | 10 | 0 | 0 | 6 | 0 |
| | | B | 0 | 12 | 0 | 0 | 6 | 0 |
| | | C | 0 | 11 | 0 | 0 | 6 | 0 |
| | | D | 0 | 11 | 0 | 0 | 6 | 0 |
| | | E | 0 | 10 | 0 | 0 | 6 | 0 |
| Damask over cotton batting | Crevice | A | 10 | 10 | 100 | 6 | 6 | 100 |
| | | B | 3 | 20 | 15 | 0 | 6 | 0 |
| | | C | 6 | 15 | 40 | 1 | 6 | 17 |
| | | D | 2 | 18 | 11 | 0 | 6 | 0 |
| | | E | 1 | 19 | 5 | 0 | 6 | 0 |
| Damask over cotton batting | Crevice with welt cord) | A | 10 | 10 | 100 | 6 | 6 | 100 |
| | | B | 0 | 20 | 0 | 0 | 6 | 0 |
| | | C | 2 | 19 | 11 | 0 | 6 | 0 |
| | | D | 1 | 20 | 5 | 0 | 6 | 0 |
| | | E | 1 | 20 | 5 | 0 | 6 | 0 |
| Heavy velvet over Foam | Cushion | A | 0 | 10 | 0 | 0 | 5 | 0 |
| | | B | 0 | 16 | 0 | 0 | 5 | 0 |
| | | C | 0 | 13 | 0 | 0 | 5 | 0 |
| | | D | 0 | 13 | 0 | 0 | 5 | 0 |
| | | E | 0 | 11 | 0 | 0 | 5 | 0 |
| Heavy velvet over cotton batting | Crevice | A | 8 | 11 | 73 | 4 | 5 | 80 |
| | | B | 0 | 20 | 0 | 0 | 5 | 0 |
| | | C | 0 | 20 | 0 | 0 | 5 | 0 |
| | | D | 0 | 20 | 0 | 0 | 5 | 0 |
| | | E | 0 | 20 | 0 | 0 | 5 | 0 |
| Heavy velvet over cotton batting | Crevice (with welt cord) | A | 2 | 12 | 17 | 4 | 5 | 80 |
| | | B | 0 | 20 | 0 | 0 | 5 | 0 |
| | | C | 0 | 20. | 0 | 0 | 5 | 0 |
| | | D | 0 | 20 | 0 | 0 | 5 | 0 |
| | | E | 0 | 20 | 0 | 0 | 5 | 0 |

## Table 3-8C. Summary of Full-Scale Furniture Test Results
(First cigarette per test only)

| Material | Location | Cig. Type | Ignitions | Tests | % | Bench-scale Comparisons: Ignitions | No. of Tests | % Ignition |
|---|---|---|---|---|---|---|---|---|
| Olefin over Foam | Cushion | A | 2 | 10 | 20 | 0 | 5 | 0 |
| | | B | 0 | 10 | 0 | 0 | 5 | 0 |
| | | C | 0 | 10 | 0 | 0 | 5 | 0 |
| | | D | 0 | 10 | 0 | 0 | 5 | 0 |
| | | E | 0 | 10 | 0 | 0 | 5 | 0 |
| | Crevice (against side-cotton batting) | A | 6 | 10 | 60 | 3 | 5 | 60 |
| | | B | 0 | 19 | 0 | 0 | 5 | 0 |
| | | C | 1 | 16 | 6 | 1 | 5 | 20 |
| | | D | 0 | 13 | 0 | 0 | 5 | 0 |
| | | E | 0 | 16 | 0 | 0 | 5 | 0 |
| | Crevice welt cord (side-with cotton batting padding) | A | 10 | 10 | 100 | 5 | 5 | 100 |
| | | B | 0 | 20 | 0 | 0 | 5 | 0 |
| | | C | 0 | 18 | 0 | 0 | 5 | 0 |
| | | D | 0 | 19 | 0 | 0 | 5 | 0 |
| | | E | 0 | 20 | 0 | 0 | 5 | 0 |
| | Crevice (Back-P.U. Foam) | A | 1 | 4 | 25 | | | |
| | | B | 0 | 4 | 0 | | | |
| | | C | 0 | 4 | 0 | | | |
| | | D | 0 | 4 | 0 | | | |
| | | E | 0 | 4 | 0 | | | |
| | Crevice with welt cord back | A | 4 | 4 | 100 | | | |
| | | B | 0 | 4 | 0 | | | |
| | | C | 0 | 4 | 0 | | | |
| | | D | 0 | 4 | 0 | | | |
| | | E | 0 | 4 | 0 | | | |

## Table 3-9. Numbers of Tests and Results Full-Scale and Bench-Scale, Various Cigarettes and Substrates

| Cig. Type | | A C-6 | | | C #129 | | | E #106 | | | D #114 | | | B #201 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Substrates | | Ign | Tot[a] | SE | Ign | Tot[a] | SE | Ign | Tot[a] | SE | Ign | Tot[a] | SE | Ign | Tot[a] | SE |
| CA,fl | FS | 12 | 0 | 12 | 12 | 1 | 13 | 5 | 0 | 12 | 10 | 0 | 12 | 9 | 0 | 12 |
| | BS | 5 | 0 | 5 | 5 | 0 | 5 | 1 | 0 | 5 | 2 | 0 | 5 | 0 | 0 | 5 |
| CA,Cr | FS | 14 | 0 | 14 | 12 | 2 | 14 | 3 | 7 | 19 | 8 | 7 | 19 | 4 | 18 | 24 |
| | BS | 5 | 0 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 1 | 4 | 5 | 0 | 5 | 5 |
| CA,Cr,wlt | FS | 10 | 0 | 10 | 7 | 8 | 5 | 0 | 14 | 18 | 2 | 12 | 17 | 0 | 18 | 19 |
| | BS | 5 | 0 | 5 | 1 | 4 | 5 | 1 | 4 | 5 | 1 | 3 | 5 | 0 | 5 | 5 |
| CA,Cr[a] | FS | 5 | 0 | 5 | 5 | 1 | 6 | 3 | 1 | 6 | 4 | 5 | 9 | 2 | 5 | 8 |
| | BS | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| Sp1,f1 | FS | 10 | 0 | 10 | 10 | 0 | 10 | 3 | 0 | 10 | 8 | 1 | 11 | 0 | 8 | 16 |
| | BS | 5 | 0 | 5 | 2 | 3 | 5 | 0 | 2 | 5 | 1 | 3 | 5 | 0 | 5 | 5 |
| Sp1,Cr | FS | 10 | 0 | 10 | 1 | 18 | 19 | 0 | 20 | 20 | 0 | 20 | 20 | 0 | 20 | 20 |
| | BS | 5 | 0 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 0 | 4 | 5 |
| Sp1,Cr,wlt | FS | 10 | 0 | 10 | 0 | 20 | 20 | 0 | 20 | 20 | 0 | 20 | 20 | 0 | 20 | 20 |
| | BS | 5 | 0 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 0 | 4 | 5 | 0 | 5 | 5 |
| Vel,fl | FS | 0 | 0 | 10 | 0 | 3 | 13 | 0 | 1 | 11 | 0 | 5 | 13 | 0 | 9 | 16 |
| | BS | 0 | 0 | 5 | 0 | 3 | 5 | 0 | 3 | 5 | 0 | 5 | 5 | 0 | 5 | 5 |
| Vel,Cr | FS | 8 | 1 | 11 | 0 | 20 | 20 | 0 | 20 | 20 | 0 | 20 | 20 | 0 | 20 | 20 |
| | BS | 4 | 0 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 0 | 5 | 5 |
| Vel,Cr,wlt | FS | 2 | 1 | 12 | 3 | 20 | 20 | 0 | 20 | 20 | 0 | 20 | 20 | 0 | 20 | 20 |
| | BS | 4 | 0 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 0 | 5 | 5 | 0 | 5 | 5 |
| Da,fl | FS | 0 | 0 | 10 | 0 | 1 | 11 | 0 | 0 | 10 | 0 | 2 | 11 | 0 | 3 | 12 |
| | BS | 0 | 0 | 6 | 0 | 2 | 6 | 0 | 1 | 6 | 0 | 3 | 6 | 0 | 4 | 6 |
| Da,Cr | FS | 10 | 0 | 10 | 6 | 9 | 15 | 1 | 18 | 19 | 2 | 16 | 18 | 3 | 17 | 20 |
| | BS | 6 | 0 | 6 | 1 | 5 | 6 | 0 | 6 | 6 | 0 | 6 | 6 | 0 | 5 | 6 |
| Da,Cr,wlt | FS | 10 | 0 | 10 | 2 | 17 | 19 | 1 | 19 | 20 | 1 | 19 | 20 | 0 | 20 | 20 |
| | BS | 6 | 0 | 6 | 0 | 6 | 6 | 0 | 6 | 6 | 0 | 5 | 6 | 0 | 5 | 6 |
| Ole,fl | FS | 2 | 0 | 10 | 0 | 0 | 10 | 0 | 0 | 10 | 0 | 0 | 10 | 0 | 10 | 17 |
| | BS | 0 | 0 | 5 | 0 | 0 | 5 | 0 | 1 | 5 | 0 | 0 | 5 | 0 | 2 | 5 |
| Ole,Cr | FS | 6 | 0 | 10 | 1 | 8 | 16 | 0 | 10 | 16 | 0 | 6 | 13 | 0 | 19 | 16 |
| | BS | 3 | 0 | 5 | 1 | 1 | 5 | 0 | 1 | 5 | 0 | 0 | 5 | 0 | 2 | 5 |
| Ole,Cr,wlt | FS | 10 | 0 | 10 | 0 | 17 | 18 | 0 | 19 | 20 | 0 | 9 | 19 | 0 | 20 | 20 |
| | BS | 5 | 0 | 5 | 0 | 4 | 5 | 0 | 4 | 5 | 0 | 5 | 5 | 0 | 5 | 5 |
| | | 177 | 4 | 242 | 66 | 198 | 317 | 18 | 222 | 329 | 40 | 215 | 330 | 18 | 286 | 361 |
| % | | 73 | | 2 | 21 | | 62 | 5 | | 67 | 12 | | 65 | 5 | | 79 |
| % Ignitions | | | | | | | | | | | | | | | | |
| Full-scale | | 73 | | | 23 | | | 6 | | | 14 | | | 6 | | |
| Bench-scale | | 74 | | | 13 | | | 3 | | | 6 | | | 0 | | |

Legend:
- Ign – means number of ignitions
- SE – means number of self-extinguishments
- Tot – means total number of tests
- CA – California velvet
- Spl – Splendor fabric
- Vel – heavy cotton velvet
- Da – damask
- Ole – olefin fabric
- fl – flat (on a cushion)
- cr – crevice
- wlt – welt cord

[a]Total tests run for a given cigarette type on a given substrate. This includes three possible results: ignition, self-extinguishment, or a cigarette burning its entire length without causing substrate ignition.
[b]crevice formed by weights on cushion

## Validation Results Weighted by Numbers of Tests

Table 3-9 presents actual results of both bench-scale and full-scale tests, arranged with substrate types as rows and cigarette types as columns. The "%" rows near the bottom of the table show first the weighted (by number of tries) percentages of ignition, then self-extinguishments, and these are compared with the weighted percentages for the full-scale tests and the bench-scale tests.

Several conclusions are obvious:

1. The percentage ignitions of the experimental cigarettes (range 7-35%) are a different population than that of the commercial No. 6 cigarette (73%). In fact, the "in-between" cigarette, #129, at 35% ignitions, is different than the three low ignition propensity cigarettes (7-11%). Recall, these data are with a variety of substrates.

2. There are no differences in conclusion no. 1 if it had been arrived at by considering bench-scale tests alone or full-scale tests alone.

3. The literature concludes that commercial cigarettes are more likely to ignite the substrate if they are located in crevices. This is also true for the commercial No. 6 cigarette in this project. But the experimental cigarettes are not more likely to ignite substrates in crevices than on flat surfaces.

4. The overall percentages of "self-extinctions" range from 0.4% for the commercial cigarette (only two of the many cigarettes and only on one substrate) to 51-69% for the experimental cigarettes. It is tempting to conclude that a major reason for the success of the experimental cigarettes is that they self-extinguished when on the substrate. However, examination of the data in Table 3-9 and the note on the table, show that there are many tests where the experimental cigarette did not self-extinguish, but still did not ignite the substrate.

5. Self-extinctions are also very much affected by the substrate and the location (flat surface, crevice, or crevice with welt cord). If the location, cigarette, and substrate are all kept constant, many cigarette types either did all self-extinguish or not self-extinguish, whether full-scale or bench-scale. With another substrate or location on the same substrate, the results could be totally different.

## Use of Kendall's Tau Correlation Coefficient to Summarize the Agreement Between Full-Scale and Bench-Scale Tests

In Appendix 3-B is a memo from Dr. Keith R. Eberhardt of the Statistical Engineering Division of NBS giving a statistical analysis of the data. Most statistical methods are difficult to apply to these data, but Dr. Eberhardt was able to test the hypothesis that there is "no relation between the full-scale data and the bench-scale data." The hypothesis was rejected at a significance level of 0.01%.

## Relative Ranking of Cigarettes in Full-Scale Tests and the Primary Evaluation

Table 3-8 summarizes the ignition results obtained in the full-scale tests. The cigarettes had been chosen on the basis of the primary evaluation to represent a high ignition propensity cigarette—commercial, No. 6, an intermediate cigarette, 129, and three low ignition propensity cigarettes, 106, 114, and 201. These rankings were fully confirmed by the full-scale results, as well as the corresponding bench-scale (mockup) results.

Table 3-9 lists the number of self-extinguishments. There were essentially none for No. 6. For the other cigarettes the results were substrate dependent, with no major differences between the four experimental cigarettes.

This seems to indicate that a common mechanism for self-extinguishment prevailed in those cigarettes, in spite of their differences in burn rates in air and other physical characteristics.

# Average Per Puff Tar, Nicotine, and CO Yields of Experimental Cigarettes

The Federal Trade Commission and Lorillard Laboratories results for per cigarette tar, nicotine, and CO yields are discussed in Section 2. Tar, nicotine and CO yields are generally used to compare commercial cigarettes. These measurements do not tell the whole story about toxic effects of other smoke constituents which could differ for the experimental cigarette and commercial cigarettes. This section deals with per puff yields of the experimental cigarettes. This is important because the number of puffs of the experimental cigarettes varied widely but could be adjusted to the commercial norm, 7 to 9 [3-9], if the cigarettes were produced commercially. It was found that one of the low ignition propensity cigarettes, BELN-21, No.106, had per puff yields comparable to the average yield of 25 per cent of U.S. commercial cigarettes. Other low ignition propensity cigarettes had higher per puff yields. The details are given below.

The per puff yields are given in Tables 3.10 and 3.11. For comparison, the average yields per puff of the six most popular cigarette packings which represent about 25 percent of the market were the following: tar, 2.0 mg; nicotine, 0.13 mg, and CO, 1.7 mg [3-22, 23]. (The puff counts for these packings were obtained from the FTC [3-25].)

The puff count can be adjusted to the norm by increasing or decreasing the cigarette length. Thus the low ignition propensity cigarette BELN-21, No. 106, with a low puff count, could be made longer, and the high puff count cigarette No.201, shorter. It should, however, be noted that the per puff yields increase as the cigarettes become shorter [3-25], so that shortening would not reduce the yields in direct proportion to the length. Nevertheless, the per puff yields results would still provide guidance for attempts to design cigarettes with both acceptable yields and low ignition propensity.

Table 3-12 shows the effects of the Series 1 cigarette design variables on per puff yields. No statistical analysis of the results is indicated in view of the above mentioned uncertainties. In general, the trends shown correspond to what would be expected from the results of research in this area [e.g., 3-26].

The design factors which reduced available tobacco, i.e., use of expanded, large particle size tobacco and smaller circumference, also reduced per puff yields as well as ignition propensity.

On the other hand, low paper permeability, which was second in importance in reducing ignition propensity, resulted in substantial increases in the per puff yields. However, it should be kept in mind that the high permeability paper in these experimental cigarettes was purposely chosen to be higher than that commonly used in most commercial cigarettes, accentuating the differences due to paper permeability in this series. Also, as mentioned before, other means for reducing yields are available.

The cigarettes containing flue-cured tobacco had higher per puff yields than the Burley cigarettes. However, the tobacco type had no significant effect on ignition propensity.

The effect of the presence of citrate in the cigarette paper appears minor for per puff yields; however, the paper of the low ignition propensity cigarettes did not contain citrate.

The tar, nicotine, and CO yields per cigarette and per puff yields of the Series 2 cigarettes (Table 3-11) decreased, in the first approximation, with increasing paper permeability, regardless of whether the increase was caused by perforation, embossing, or both. The ignition propensity increased with increasing permeability. Addition of the highly permeable, thin second paper layer had only little effect on yields or ignition propensity.

## Table 3-10. Per Puff Tar, Nicotine and Carbon Monoxide Yields of Series 1 Experimental Cigarettes

| | | | Per Puff Yield | | | Burn Rate[b] | |
|---|---|---|---|---|---|---|---|
| Cigarette Number | Ignitions | Packing density | Tar mg[a] | Nic. mg[a] | CO mg[a] | linear mm/min | mass mg/min |
| 101 | 13 | 0.24 | 2.47 | 0.18 | 2.73 | 5.79 | 54.9 |
| 102 | 12 | 0.25 | 2.75 | 0.20 | 2.63 | 4.80 | 45.6 |
| 103 | 17 | 0.25 | 1.76 | 0.16 | 1.89 | 7.42 | 71.5 |
| 104 | 19 | 0.24 | 2.03 | 0.18 | 1.76 | 6.82 | 64.4 |
| 105 | 6 | 0.16 | 1.55 | 0.09 | 1.90 | 7.77 | 47.2 |
| 106 | 1 | 0.17 | 1.83 | 0.10 | 2.00 | 6.58 | 39.8 |
| 107 | 11 | 0.17 | 1.03 | 0.07 | 1.03 | 9.99 | 59.6 |
| 108 | 7 | 0.14 | 1.25 | 0.09 | 1.07 | 8.89 | 53.3 |
| 109 | 15 | 0.31 | 2.50 | 0.21 | 1.96 | 4.46 | 49.4 |
| 110 | 16 | 0.31 | 2.19 | 0.19 | 1.56 | 3.40 | 40.3 |
| 111 | 19 | 0.32 | 1.92 | 0.18 | 1.44 | 5.30 | 62.3 |
| 112 | 20 | 0.31 | 1.84 | 0.17 | 1.23 | 4.96 | 57.9 |
| 113 | 6 | 0.15 | 2.41 | 0.19 | 2.24 | 7.34 | 42.4 |
| 114 | 4 | 0.15 | 2.58 | 0.21 | 2.12 | 5.52 | 33.8 |
| 115 | 14 | 0.17 | 1.72 | 0.14 | 1.55 | 8.99 | 55.2 |
| 116 | 12 | 0.15 | 1.88 | 0.16 | 1.25 | 7.58 | 45.6 |
| 117 | 18 | 0.24 | 2.62 | 0.20 | 3.21 | 5.84 | 72.5 |
| 118 | 18 | 0.24 | 2.84 | 0.22 | 2.84 | 4.78 | 58.9 |
| 119 | 20 | 0.23 | 2.08 | 0.18 | 2.34 | 7.60 | 93.1 |
| 120 | 20 | 0.23 | 2.14 | 0.19 | 1.79 | 6.72 | 83.2 |
| 121 | 14 | 0.14 | 2.14 | 0.13 | 2.68 | 8.11 | 61.2 |
| 122 | 7 | 0.13 | 2.42 | 0.15 | 2.42 | 6.38 | 46.8 |
| 123 | 15 | 0.14 | 1.48 | 0.09 | 1.85 | 10.63 | 78.2 |
| 124 | 15 | 0.14 | 1.55 | 0.10 | 1.38 | 9.12 | 67.6 |
| 125 | 18 | 0.28 | 2.46 | 0.21 | 1.92 | 4.05 | 61.7 |
| 126 | 17 | 0.28 | 2.46 | 0.20 | 1.74 | 3.46 | 51.1 |
| 127 | 20 | 0.28 | 2.23 | 0.21 | 1.79 | 5.08 | 75.5 |
| 128 | 20 | 0.29 | 2.41 | 0.21 | 1.52 | 4.58 | 69.1 |
| 129 | 10 | 0.16 | 2.26 | 0.18 | 2.02 | 5.17 | 44.2 |
| 130 | 4 | 0.16 | 2.50 | 0.20 | 2.16 | 3.88 | 33.6 |
| 131 | 15 | 0.21 | 0.96 | 0.08 | 0.87 | 6.43 | 61.9 |
| 132 | 12 | 0.16 | 1.90 | 0.17 | 1.31 | 5.27 | 45.1 |

(a) Based on FTC data.
(b) Data from the Lorillard Laboratories (see Table 2-5)

## Table 3-11. Per Puff Tar, Nicotine and Carbon Monoxide Yields of Series 2 Experimental Cigarettes

| Cigarette Number | Ignitions | Packing density mg/mm³ | Per puff yields, mg[a] Tar | Nic. | CO |
|---|---|---|---|---|---|
| 201 | 0 | 0.14 | 2.5 | 0.18 | 2.5 |
| 202 | 2 | 0.16 | 2.0 | 0.16 | 2.4 |
| 203 | 7 | 0.15 | 1.7 | 0.14 | 1.8 |
| 204 | 11 | 0.16 | 1.3 | 0.11 | 1.2 |
| 205 | 11 | 0.16 | 1.2 | 0.11 | 1.0 |
| 206 | 8 | 0.16 | 2.4 | 0.18 | 3.2 |
| 207 | 7 | 0.16 | 1.9 | 0.15 | 2.3 |
| 208 | 14 | 0.16 | 1.6 | 0.13 | 1.7 |
| 209 | 13 | 0.16 | 1.4 | 0.12 | 1.5 |

(a) Based on FTC data

Burn rates not available

## Table 3-12. Per Puff Tar, Nicotine and CO Yields as a Function of Cigarette Parameters

Experimental Cigarette Series 1

| Cigarette parameters | Per Puff Yields (mg) Tar | Nicotine | Monoxide | Number of Ignitions |
|---|---|---|---|---|
| Tobacco Packing Density | | | | |
| High | 2.29 | 0.19 | 2.02 | 282 |
| Low | 1.84 | 0.13 | 1.74 | 153 |
| Paper Permeability | | | | |
| High | 1.76 | 0.15 | 1.50 | 256 |
| Low | 2.37 | 0.18 | 2.26 | 179 |
| Cigarette Circumference (mm) | | | | |
| 25 | 2.15 | 0.17 | 1.99 | 243 |
| 21 | 1.98 | 0.16 | 1.77 | 192 |
| Paper Citrate Conc. (%) | | | | |
| 0.8 | 1.97 | 0.16 | 1.96 | 231 |
| 0.0 | 2.16 | 0.17 | 1.80 | 204 |
| Tobacco Type | | | | |
| Flue-cured | 2.14 | 0.18 | 1.67 | 222 |
| Burley | 2.00 | 0.15 | 2.10 | 213 |

# Summary of Characteristics of Experimental, Low Ignition Propensity Cigarettes

Table 3-13 compares ignition propensities and certain other characteristics of selected experimental cigarettes from Series 1 and Series 2. For comparison, the results are included for three commercial cigarette packings; one, No. 6, had been found to have typical (for current production) ignition propensity and No.2, slightly lower than typical ignition propensity in the previous investigation [3-3]. Not all cigarettes were tested on all substrates; cigarettes for this work were selected over a period of many months during which time the interest in various cigarette design variables was subject to change as various findings were made. The following can be deduced from the data:

- The selected low ignition propensity experimental cigarettes had considerably lower ignition propensity when tested on a wide variety of substrates, including some with very low cigarette ignition resistance, than even the relatively low ignition propensity commercial cigarette packing.
- The ignition propensity rankings of the cigarettes were approximately the same on all substrates.
- The low ignition propensity experimental cigarettes covered a wide range of linear burn rates in air. It had generally been assumed that only cigarettes with low burn rates – causing self-extinguishment in air – could have a

## Table 3-13. Summary of Characteristics of Selected Cigarettes

| | Number of Ignitions (%) | | | | Burn Rates[c] | | Per Puff Smoke Yields[f] | | |
|---|---|---|---|---|---|---|---|---|---|
| Cigarette No. | Primary Eval.[a] | HA CB/PU[b] | Full-Scale[c] | Comparable Mockups[d] | Linear mm/min | Mass mg/min | Tar (mg) | Nicotine (mg) | CO (mg) |
| 106 BELN-21 | 5 | 10 | 10 | 3 | 6.58 | 39.8 | 1.83 | 0.10 | 2.00 |
| 114 FELN-21 | 20 | 10 | 7 | 6 | 5.52 | 33.8 | 2.58 | 0.21 | 2.12 |
| 129 FELC-25 | 50 | – | 35 | 13 | 5.12 | 44.2 | 2.26 | 0.18 | 2.02 |
| 130 FELN-25 | 20 | 30[g] | – | – | 3.88 | 33.6 | 2.50 | 0.20 | 2.16 |
| 201 | 0 | 10[g] | 11 | 0 | – | – | 2.5 | 0.18 | 2.5 |
| Commercial | | | | | | | | | |
| 1 | 80[h] | – | – | – | – | – | – | – | – |
| 2 | 60[h] | 100 | – | – | – | – | – | – | – |
| 3 | 90[i] | – | – | – | – | – | – | – | – |
| 6 | 100[i] | 100 | 74 | 74 | – | – | – | – | – |

(a) 20 tests
(b) 10 tests
(c) Variable numbers tests
(d) 105 tests
(e) Data from the Lorillard Laboratories
(f) Based on FTC data
(g) Many of these cigarettes self-extinguished on these substrates
(h) Found to have relatively low ignition propensity in [3-3]
(i) Found to have normal ignition propensity in [3-3]



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low ignition propensity [3-14]. The experimental low ignition propensity cigarette with the lowest burn rate, FELN-25, No. 130, often self-extinguished on some of the substrates while other replicates burned their whole length, in most cases without causing smoldering ignitions. Cigarette 202 also tended to self-extinguish in air. However, the low ignition propensity cigarette BELN-21, No. 106, had a high linear burn rate, and did not self-extinguish in air.

- One of the low ignition propensity cigarettes, BELN-21, No. 106, had considerably lower per puff tar, nicotine, and CO yields than the other low ignition propensity cigarettes.
- As discussed in detail in Section 4, it appears that lessened heat transfer to a substrate can be caused by reduction in heat output of cigarettes due to partial blocking of oxygen influx by the substrate, as well as by the substrate heat sink effect. If the heat output rate is low because of low tobacco content per unit length, or if the oxygen supply (which is already partially blocked by the substrate) is further restricted by low permeability paper, or by a combination of both factors, low ignition propensity can be achieved, even though the cigarette does not self-extinguish in air. Other factors, such as generation of smoldering inhibiting gases including water vapor and carbon dioxide may also play a role [3-27].

## Table 3-14. Ignition Propensity of Patented Cigarettes

| Cigarette | Burns in air | weight (g) | Substrates HA/CB | HA/PU | SPL/PU | CA/CB | CA/CB[a] | Total Ign. (%) |
|---|---|---|---|---|---|---|---|---|
| 301-C | yes | 1.06 | 5/5 | 5/5 | 5/5 | 5/5 | 5/5 | 100 |
| 301 | yes | 1.10 | 8/10 | 1/10 | 5/10 | 7/10 | 8/10 | 58 |
| 302-C | yes | 0.93 | 5/5 | 5/5 | 5/5 | 5/5 | 4/5 | 96 |
| 302 | no | 0.94 | 3/10 | 2/10 | 2/10 | 1/10 | 2/10 | 20 |
| 303-C | yes | 0.99 | 5/5 | 5/5 | 5/5 | 5/5 | 5/5 | 100 |
| 303 | yes | 0.98 | 6/10 | 0/10 | 2/10 | 18/20 | 6/10 | 53 |
| 304-C | yes | 1.14 | 5/5 | 5/5 | 5/5 | 5/5 | 5/5 | 100 |
| 304 | yes | 1.18 | 9/10 | 8/10 | 10/10 | 4/10 | 2/10 | 66 |
| 305-C | yes | 0.99 | 5/5 | 5/5 | 5/5 | 5/5 | 5/5 | 100 |
| 305 | no | 1.00 | 3/20 | 4/10 | 3/10 | 1/10 | 2/10 | 22 |

All tests on flat substrate; some cigarettes with firestops self-extinguished on mockups.
Fabrics: HA – Haitian cotton
SPL – Splendor
CA – California standard
Padding: CB – Cotton batting
PU – Polyurethane foam
Cigarettes: C – Controls submitted with patented cigarettes

(a) a half of tobacco column removed

# Patented Cigarettes

The ignition propensities of five embodiments of patented cigarettes and of the controls submitted with each of them were evaluated. In short, it was found that all the embodiments showed improvement over those designated as controls. The details are discussed below.

The patented cigarette embodiments and the controls submitted with them were tested in three of the modes used in the primary evaluation. Instead of evaluating them on the relatively high ignition resistance denim substrate which had been used in the primary evaluation, they were tested on the very low cigarette ignition resistance Haitian cotton substrates.

Table 3-14 shows the ignition results. When the patented cigarettes showed poor reproducibility, the number of cigarettes tested was increased. The number of ignitions is presented as a percentage of total possible ignitions.

All of the cigarettes submitted as controls caused essentially 100 percent ignitions.

The patented cigarettes caused ignition in 20 to 66 percent of the cases. The overall differences between the patented cigarettes and the controls were significant at the 0.01 percent level. (A method suggested by Cochran for combining information in 2 × 2 tables was used in this analysis [3-28].) The information submitted by the inventors indicates that only limited development work had been performed prior to submission of the cigarettes in most cases; further improvements may be possible.

Two patented cigarettes used the firestop concept by placing obstacles in the path of the smolder front. These cigarettes self-extinguished at their firestops when burning in air, and, in our experiments, also on the substrates. Unless puffed at such firestops, the cigarette will go out. If the number of firestops is too small, the cigarette may ignite the substrates; smoldering ignition of substrates can occur in as little as 2 minutes [3-29].

# Summary and Conclusions

The propensities to ignite soft furnishings substrates of 41 systematically varied experimental cigarettes and five patented cigarettes were compared to those of commercial cigarettes. Some experimental and patented cigarettes performed distinctly better.

A combination of low tobacco content per unit length (low packing density and low circumference of the cigarettes) and low paper permeability and paper citrate content produced cigarettes which did not ignite most substrates used in our experiments. These substrates included some which. on the basis of a large number of investigations [summarized in [3-20], would be expected to have very low cigarette ignition resistance and which were readily ignited by commercial cigarettes, even one which had previously been found to have relatively low ignition propensity. One could expect the proportion of upholstered furniture which would be ignited by the low ignition propensity experimental cigarettes to be small.

The low ignition propensity of these cigarettes was demonstrated under a wide variety of conditions which could occur in real life. These included full-scale chair tests, as well as a large number of bench-scale tests on substrates in the lower cigarette ignition resistance range; on flat surfaces and in crevices of various configurations; and on full length cigarettes and on short cigarettes, simulating partially smoked cigarettes. Similarly, low ignition propensity of the same cigarette was demonstrated, albeit less clearly, in limited experiments on new fabric and on fabrics which had been intentionally contaminated with smolder-promoting agents, as well as on fabrics badly soiled in use. However, no claim can be made that the present experimental cigarettes would prevent all cigarette initiated fires. Based on the fact that they did not readily ignite substrates which have very low ignition propensity, one could expect that the number of soft furnishings in use which would be ignited by them would be small. High ambient air velocity may increase ignition propensity. However, the number of such cigarette-caused ignitions would clearly be reduced.

Another important finding is that low ignition propensity does not necessarily lead to unacceptably high tar, nicotine and CO yields as had been proposed [e.g., 3-14].

The five patented cigarettes which were submitted by their inventors exhibited various levels of ignition propensity, all significantly lower than the controls submitted with them. From the present results, it is not possible to state which of the invention concepts would give the best results.

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# Appendix 3-A
# Statistical Analysis of Ignition Propensity Data for Series #1 Experimental Cigarettes

**Prepared by Keith R. Eberhardt**

## Analysis of Variance for Table 3.1

The data in Table 3.1 constitute a complete 25 factorial design for each of the four substrates.

To adjust for the fact that the basic data in Table 3.1 are count data, and thus not normally distributed, the response variable used in the analysis was obtained by using the Freeman-Tukey modification of the commonly used angular transformation [3-6]. The formula is

```
Y = 0.5*{ ARCSIN( SQRT(IGNS/6) ) +
                    ARCSIN( SQRT((IGNS+1)/6) ) }
```

where IGNS denotes the number of ignitions (out of 5 trials).

After transformation, the data were analyzed by standard Analysis of Variance (ANOVA) methods [3-7]. The results of the ANOVA are presented graphically in Figures 3-A-1 through 3-A-4, and are summarized numerically in the table.

Figures 3-A-1 through 3-A-4 and the table show that two factors, namely, Packing Density and Permeability, were

**Table 3-A-1. Significance Probabilities (in Percent) of Design Factors for Series #1 Cigarettes**
**(Experimental error was estimated from 4- and 5-way interactions.)**

| | Substrate | | | |
|---|---|---|---|---|
| | CA/CB unc./flat | SPL/PU unc./flat | SPL/PU unc./flat (½ cig.) | Denim/PU crev./cov. |
| **Factors** | | | | |
| D (Packing Density) | 0.05 | 0.10 | 0.01 | 0.01 |
| P (Permeability) | 0.08 | 0.23 | 0.69 | 0.01 |
| R (Circumference) | 0.03 | 85 | 2.7 | 0.01 |
| C (Citrate Conc.) | 25 | 2.0 | 0.69 | 7.6 |
| T (Tobacco Type) | 8.9 | 52 | 56 | 7.6 |
| **Interactions** | | | | |
| D*P | 1.55 | 0.23 | 0.69 | 0.01 |
| D*R | 0.45 | 85 | 2.7 | 0.01 |
| D*C | 43 | 2.0 | 0.69 | 7.6 |
| D*T | 45 | 52 | 56 | 7.6 |
| P*R | 0.93 | 52 | 39 | 5.5 |
| P*C | 45 | 6.6 | 85 | 21 |
| P*T | 17 | 85 | 7.4 | 21 |
| R*C | 29 | 85 | 62 | 2.2 |
| R*T | 8.9 | 3.8 | 2.8 | 2.2 |
| C*T | 45 | 52 | 62 | 81 |

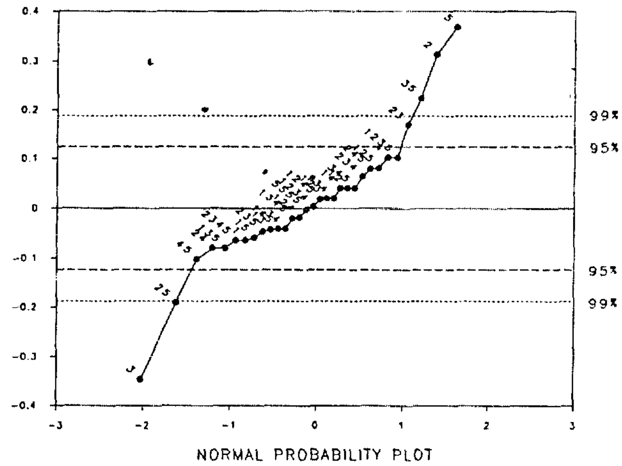



**Figure 3-A-1. Normal probability plot of estimated factorial effects from a $2^5$ factorial analysis of variance for the substrate CA/CB, unc./flat.** **If none of the factorial effects were significant, the data would cluster about a single straight line on the plot. The factors are coded as: 1 = Citrate, 2 = Paper permeability, 3 = Packing density, 4 = Tobacco type (Burley or flue-cured), 5 = Circumference (21 mm vs. 25 mm). The indicated 95% and 99% limits on the plot are computed using the 4- 5-way interaction terms to estimate experimental error. These limits correspond, respectively, to 5% and 1% tests of the hyopthesis that the factorial effects are zero.**

highly significant consistently across all four substrates. Two additional factors, Circumference and Citrate Concentration, showed clear significance in two of the four substrates. The factor for Tobacco Type (i.e. burley vs. flue-cured) did not show a significant effect on number of ignitions on any of the four substrates.

The interactions among these factors were frequently significant whenever the factors were. Generally, the presence of a significant interaction indicates that the magnitude of the effect on ignition propensity for an given factor is not constant across the levels of the interacting factor. For example, on the CA/CB substrate, the significant interaction between Packing Density and Circumference indicates that the effect of Packing Density on ignition propensity is different in magnitude for the smaller circumference cigarettes than for the larger circumference cigarettes in the experiment. Detailed study of the data suggests that many of the significant interactions can be explained by the single fact that the maximum number of ignitions per test condition could not exceed five in this experiment, thus limiting the possible magnitudes of the estimated effects.

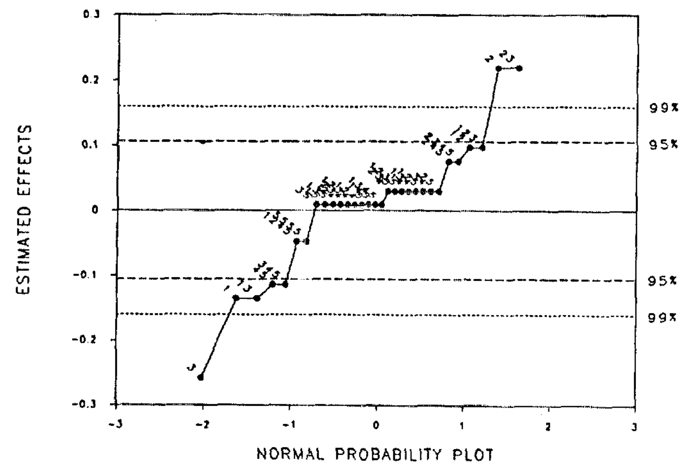



**Figure 3-A-2. Normal probability plot of estimated factorial effects from a $2^5$ factorial analysis of variance for the substrate SPL/PU, unc./flat.** **If none of the factorial effects were significant, the data would cluster about a single straight line on the plot. The factors are coded as: 1 = Citrate, 2 = Paper permeability, 3 = Packing density, 4 = Tobacco type (Burley or flue-cured), 5 = Circumference (21 mm vs. 25 mm). The indicated 95% and 99% limits on the plot are computed using the 4- and 5-way interaction terms to estimate experimental error. These limits correspond, respectively, to 5% and 1% tests of the hypothesis that the factorial effects are zero.**

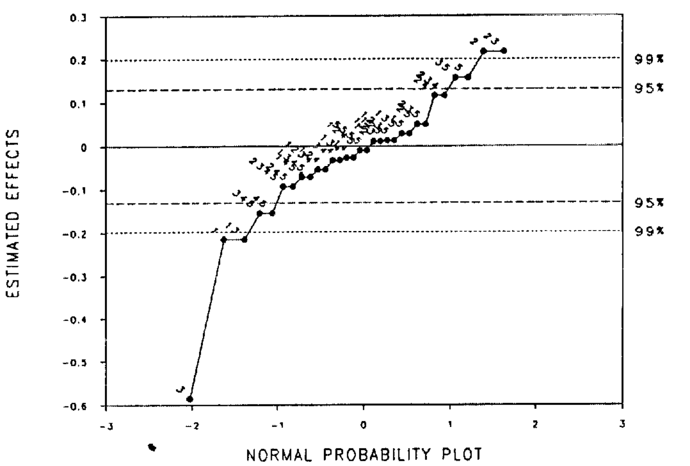
## Effect of Shortened Cigarettes

The two substrates on SPL/PU differ only in that the cigarettes used had half of the tobacco column removed in one case. This provides information on the effect of length of the tobacco column. The data were analyzed in two ways to test for a significant effect of the "Length" factor.

*Sign Test.* Of the 32 cigarette packings studied, 22 had the same number of ignitions on SPL/PU for the whole and shortened cigarettes. The remaining 10 had fewer ignitions for the shortened cigarettes. Using a sign test [3-8] to evaluate the statistical significance of this result yields a (2-sided) p-value of 0.2%. This reflects strong evidence that shortened cigarettes have a lower ignition propensity on this substrate.

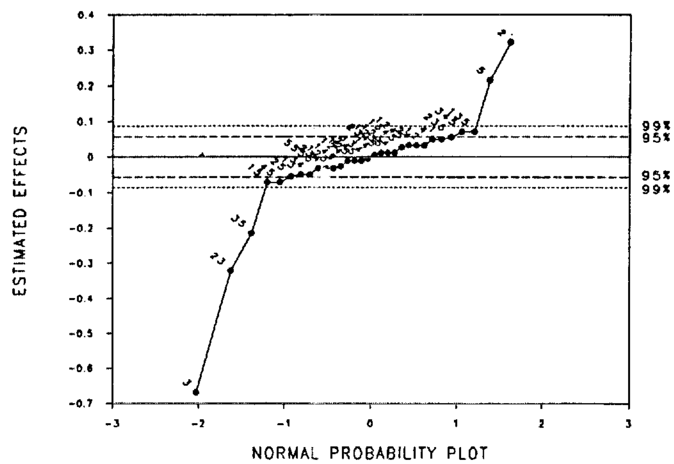
*ANOVA.* The subtable obtained from Table 3.1 by considering only the two SPL/PU substrates has $2^6$ factorial structure. However, since all of the cigarettes in the subtable with high packing density had 5 out of 5 ignitions, there is

**Figure 3-A-3. Normal probability plot of estimated factorial effects from a $2^5$ factorial analysis of variance from the substrate SPL/PU* (one half of tobacco column removed, unc./flat.** If none of the factorial effects were significant, the data would cluster about a single straight line on the plot. The factors are coded as: 1 = Citrate, 2 = Paper permeability, 3 = Packing density, 4 = Tobacco type (Burley or flue-cured), 5 = Circumference (21 mm vs. 25 mm). The indicated 95% and 99% limits on the plot are computed using the 4- and 5-way interaction terms to estimate experimental error. These limits correspond, respectively, to 5% and 1% tests of the hypothesis that the factorial effects are zero.




no information about the effect of shortened cigarettes in that portion of the data. Thus, the relevant subtable extracted from Table 3.1 includes only cigarettes with low packing density. The remaining factors, Permeability, Circumference, Citrate Concentration, Tobacco Type, and Length (whole vs. half), form a complete $2^5$ factorial experiment. An ANOVA

**Figure 3-A-4. Normal probability plot of estimated factorial effects from a $2^5$ factorial analysis of variance from the substrate Denim/PU, crev./cov.** If none of the factorial effects were significant, the data would cluster about a single straight line on the plot. The factors are coded as: 1 = Citrate, 2 = Paper permeability, 3 = Packing density, 4 = Tobacco type (Burley or flue-cured), 5 = Circumference (21 mm vs. 25 mm). The indicated 95% and 99% limits on the plot are computed using the 4- and 5-way interaction terms to estimate experimental error. These limits correspond, respectively, to 5% and 1% tests of the hypothesis that the factorial effects are zero.




similar to the main analysis described in Section 3-A.1 was performed. This analysis showed that the three factors, Permeability, Citrate Concentration, and Length, were all significant with p-values less than 1.0%. For evaluating the significance of the Length factor, this result is agrees with the (simpler) sign test described above.

# Appendix 3-B

APPENDIX 3-B

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Gaithersburg, Maryland 20899

August 26, 1987

MEMORANDUM FOR John Krasny
Center for Fire Research

From: Keith R. Eberhardt
Statistical Engineering Division

Subject: Use of Kendall's Tau Correlation Coefficient to Summarize the Agreement Between Full-Scale and Bench-Scale Ignition Tests

This is to comment on how to summarize the agreement between the full-scale (FS) and bench-scale (BS) ignition tests listed in the attached table. The table contains comparisons between FS and BS results for five cigarettes and 15 substrates. (The 16th substrate listed, CA Std./deep crevice, has no bench-scale data.) The basic question about these data is whether, and to what extent, the FS and BS data can be said to agree.

In seeking inspiration for what to do with these data, I had the benefit of some very useful discussions with Stefan Leigh, Carroll Croarkin and Jim Filliben.

When I put the data on the computer, I first re-calculated the percentages in your table from the raw data you supplied. There were several differences between the summary table and my calculations. These are marked on the attached copy, and the corrected values were what I used subsequently.

To summarize the agreement between FS and BS ignition percentages, I have used the Kendall's Tau Correlation Coefficient. This choice was made partly because the data are not normally distributed. Kendall's Tau correlation coefficient is sensitive to the agreement (between the FS and BS methods) of the relative rankings of the ignition percentages for various test conditions. In the rightmost column of the attached table, I have written-in the values of Kendall's Tau for each substrate. At the bottom is the value for all data combined. In this instance, I think the best overall summary of the correlation is the combined value, which is $\tau = 0.73$.

Kendall's Tau can be used to carry out a statistical significance test of the hypothesis that the FS and BS values are unrelated. For these data, with $\tau = 0.73$, the hypothesis of no relationship is rejected at a significance level of 0.01%. This indicates that the data provide strong evidence against the hypothesis of zero correlation. As you know, strong evidence of nonzero correlation is not the same as evidence of strong correlation, so this result must be interpreted carefully. In addition, while $\tau$ is like the ordinary (Pearson) correlation coefficient in that its value is always between -1 and +1, it has other characteristics that are quite different from the Pearson correlation.

In the present context, a careful statement of the null hypothesis of "no relationship" between FS and BS results is the following. (I am using the term "test conditions" to denote all the $5 \times 15 = 75$ experimental conditions as defined by substrate and cigarette type that are summarized in the table.)

> Rank the test conditions from lowest to highest according to the percentage of ignitions recorded for the FS tests. Then the null hypothesis states that all possible rankings of those same test conditions by the respective BS results are equally likely. The calculated p-value of 0.01% indicates that, if this null hypothesis were correct, there would be a very small chance that the ranks of the BS results would be as consistent with the ranks of the FS results as they were in these data. (The roles of FS and BS test results can be reversed in this statement without changing its mathematical implications.)

A reference for Kendall's Tau is: Maurice G. Kendall, Rank Correlation Methods, 2nd edition, London: Charles Griffin & Co., 1955, pp. 4-8, 34-35, 49-53.

## Table 3-B-1. Use of Kendall's Tau Correlation Coefficient to Summarize the Agreement Between Full-Scale and Bench-Scale Ignition Tests

| Materials | | | | | | Ignitions (percent) Cigarette Designation | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fabric | Cushions | Side or Back | Welt Cord | Configuration | Test Mode | C86 (A) | 129 (C) | 106 (E) | 114 (D) | 201 (B) | Kendall's τ |
| CA Standard | CB | – | no | flat | FS | 100 | 92 | 42 | 83 | 75 | |
| | | | | | BS | 100 | 100 | 20 | 40 | 0 | 0.74 |
| CA Standard | CB | CB | no | crevice | FS | 100 | 86 | 16 | 42 | 17 | |
| | | | | | BS | 100 | 0 | 0 | 20 | 0 | 0.60 |
| CA Standard | CB | CB | yes | crevice | FS | 100 | 47 | 0 | 12 | 0 | |
| | | | | | BS | 100 | 20 | 20 | 20 | 0 | 0.76 |
| CA Standard | CB | CB | no | crevice[a] | FS | 100 | 100 | 60 | 80 | 40 | |
| | | | | | BS | | | | | | – |
| Splendor | PU | – | no | flat | FS | 100 | 100 | 30 | 73 | 0 | |
| | | | | | BS | 100 | 40 | 0 | 20 | 0 | 0.89 |
| Splendor | PU | PU | no | crevice | FS | 100 | 5 | 0 | 0 | 0 | |
| | | | | | BS | 100 | 0 | 0 | 0 | 0 | 0.76 |
| Splendor | PU | PU | yes | crevice | FS | 100 | 0 | 0 | 0 | 0 | |
| | | | | | BS | 100 | 0 | 0 | 0 | 0 | 1.00 |
| Heavy Velvet | PU | – | no | flat | FS | 0 | 0 | 0 | 0 | 0 | |
| | | | | | BS | 0 | 0 | 0 | 0 | 0 | – |
| Heavy Velvet | PU | CB | no | crevice | FS | 73 | 0 | 0 | 0 | 0 | |
| | | | | | BS | 80 | 0 | 0 | 0 | 0 | 1.00 |
| Heavy Velvet | PU | CB | yes | crevice | FS | 17 | 0 | 0 | 0 | 0 | |
| | | | | | BS | 80 | 0 | 0 | 0 | 0 | 1.00 |
| Damask | PU | – | no | flat | FS | 0 | 0 | 0 | 0 | 0 | |
| | | | | | BS | 0 | 0 | 0 | 0 | 0 | – |
| Damask | PU | CB | no | crevice | FS | 100 | 40 | 5 | 11 | 15 | |
| | | | | | BS | 100 | 17 | 0 | 0 | 0 | 0.84 |
| Damask | PU | CB | yes | crevice | FS | 100 | 11 | 5 | 5 | 0 | |
| | | | | | BS | 100 | 0 | 0 | 0 | 0 | 0.67 |
| Olefin | PU | – | no | flat | FS | 20 | 0 | 0 | 0 | 0 | |
| | | | | | BS | 0 | 0 | 0 | 0 | 0 | – |
| Olefin | PU | CB | no | crevice | FS | 60 | 6 | 0 | 0 | 0 | |
| | | | | | BS | 60 | 20 | 0 | 0 | 0 | 1.00 |
| Olefin | PU | CB | yes | crevice | FS | 100 | 0 | 0 | 0 | 0 | |
| | | | | | BS | 100 | 0 | 0 | 0 | 0 | 1.00 |

(a) Deep Crevice
CB – Cotton Batting
FS – Full-Scale

PU – LAP 2045 Polyurethane Foam
BS – Bench-Scale

combined:
τ = 0.73
(p-value = 0.01%)

The Effect of
Cigarette Characteristics
on the Ignition
of Soft Furnishings

## Section 4

# Thermophysics of the Ignition Process

## Contents for Section 4



## List of Tables

## List of Figures

# Introduction

In this section the emphasis is on the interaction between the cigarette and an upholstery substrate which may ultimately lead to smoldering combustion of the substrate or one of its components. The problem will be broken into two parts. First, the focus will be on the cigarette as a heat source for any object in contact with it; this contact will be seen to alter the cigarette coal and thus the heat flux pattern it imposes on any substrate. Second, the focus is more briefly directed to the impact of cigarette contact on an upholstery substrate and how this may lead to smolder initiation. The overall objectives in examining these two aspects of the cigarette ignition problem are: (1) To gain insight into the factors that cause the varying ignition propensities of cigarettes seen in the previous section; this may aid in the future development of cigarettes with further lessened ignition propensity. (2) To help clarify the important physics in the ignition process so as to guide the modeling results described in the next section.

The splitting of the problem into two parts, as noted above, implies that the role of interactions between the two elements (cigarette and substrate) is assumed not to be very strong. As Salig has shown, the interaction ultimately becomes considerable once the cigarette and fabric are smoldering together; they are competing for the same oxygen supply and the cigarette coal[1] is, as a result, substantially altered [4-1]. To avoid this complication, the emphasis here is on the time up to the initiation of smolder in the fabric char.[2] In many (but not all) cases, this initiation event implies that the substrate (or at least the fabric) will thereafter be consumed by self-sustained smoldering (even if the cigarette is removed after it initiates fabric smolder); cases where initiation of self-sustaining substrate (or fabric) smolder requires the extensive interaction of a cigarette coal and the fabric char beneath it are thus not considered here. By the same token, substrates which consist of a non-smoldering fabric over a smolder-prone filling material (e.g., a thermoplastic fabric over cotton batting) are not considered here.

The sequence of events that is considered here can be briefly described as follows. A cigarette initially in a steady-state, free burn condition is brought abruptly into contact with an upholstery substrate (usually a cellulosic fabric on a polyurethane foam for the tests in this section). The surface of the cigarette coal sees a radially non-symmetrical alteration in its heat exchange with the surroundings and in its oxygen influx. Initially the adjacent substrate surface is cold and so draws heat from the closest portion of the coal; at the same time the oxidation process in the coal, being a sink for gaseous oxygen, draws oxygen out of the pores in the substrate. As the substrate heats it may eventually become a relative insulator to the contacted portion of the coal, permitting less heat loss locally from the cigarette coal than would exist in free burn. The oxygen depletion in the substrate tends toward a constant level. Substrate heating continues in response to the hot coal which is slowly propagating in the direction of the cigarette axis. Heat transport in the substrate (in all directions away from the hottest point) occurs at a rate which is comparable to the coal propagation velocity (smolder velocity) and so there is a tendency for heat to accumulate more rapidly in the direction of coal movement. The substrate beneath the moving coal thus becomes hot enough to begin to react chemically. For a cellulosic fabric the first stage of reaction degrades the cellulose to a char; the polyurethane foam beneath the fabric degrades similarly but it also tends to shrink locally in the process. The foam used in this study never reached a condition of active smoldering during the time that the cigarette continued to burn; this apparently required a longer exposure to a large area of smoldering fabric. The char from at least some of the fabrics used here was capable of initiation to a state of active, self-propagating smolder based on the heat released from char oxidation; as noted above, achievement of this state signalled the end of the interval examined here.

The present examination of the heat flux pattern imposed on a substrate by a given cigarette is based on the premise that the characteristics of this pattern (e.g., peak flux, width of the flux pattern, rate of flux pattern movement) largely

[1] *The word coal as used in this chapter refers to the hot, ash-covered region beyond the paper burn line. The principal concern here is with the peripheral surface of this coal since it is the immediate heat source for the heat flux seen by the substrate. Of course, this heat originates within the bulk volume of the coal so that events within the coal interior dictate the heat available at the surface. Section 5 examines this relationship in much greater detail.*

[2] *Unless otherwise stated, "ignition" in this section refers to this more restricted event of the initiation of rapid oxidation in the fabric char.*

determine whether self-sustaining smolder (when possible) is initiated in the fabric char. Of course, the fabric characteristics count as well since, as will be seen, they can have some influence on the cigarette coal, but the flux pattern is presumed to respond primarily to the design parameters of the cigarette.

In probing this interval up to fabric ignition, the cigarette is to be examined separately as a heat source. The above discussion indicates that, even prior to the initiation of smoldering in the fabric char, the presence of the substrate has had some impact on the cigarette coal; this must be taken into account. Similarly, in probing the response of a substrate to a cigarette coal, the cigarette must be allowed to adapt to the presence of the substrate.

There are several objectives in examining the interval prior to fabric char ignition. The first is to obtain a quantitative measure, to the extent possible, of the heat flux transmitted from the cigarette coal and incident on a substrate. The second is to measure the variability of this flux with cigarette parameters. The third is to ascertain the extent to which these measurements explain the observed variability in ignition tendency as seen in substrate ignition tests with the experimental cigarettes. In general, these objectives have been successfully achieved, although there are a number of complications and limitations that have been encountered in their pursuit, as will be explained below.

In pursuing these objectives, we have been led to examine other aspects of the cigarette/substrate interaction. These include the length of the coal and its variation with both cigarette design and the configuration of an adjacent substrate, the spacing or gap between the coal and the substrate surface, and the depletion of oxygen beneath the fabric surface induced by a smoldering cigarette coal on top of it. All of these factors have some impact on the cigarette ignition problem; the most important, because it is coupled to the flux distribution from the coal, is the coal length.

# Experimental Methods

## Experimental Methods for Heat Transfer Measurement

All available methods for measuring the heat flux from an object are intrusive, i.e., they make contact with the object and thereby extract some heat from it during the measurement process. Since a burning cigarette is evolving heat at a low rate, it is readily disturbed by this heat extraction which in turn alters the measured heat flux. The situation is worse than might be inferred from the total heat evolution rate of the coal; what counts most is the heat content and heat evolution rate in the small portion of the coal which is in contact with the flux measuring device, together with the rate of heat transport in the coal itself. These complexities make it impossible to calculate the degree of disturbance but they certainly imply that the flux-measuring device must be as small as possible. The need for small size also follows from the desire to obtain good spatial resolution of the distribution of heat flux from a cigarette coal. Generally, small size brings other complications, however, such as decreased sensitivity of the measuring device. There are other considerations as well; it is highly desirable to be able to scan the spatial distribution of heat flux rapidly to facilitate acquisition of enough data to assess the variability of a given type of cigarette.

### Previous Work

There have been at least two previous efforts to characterize the heat flux from cigarettes. Behnke [4-2] examined the peak heat flux from 16 commercial cigarettes. He used a thin sheet of copper with a thermocouple on the back as an integrator of the incoming flux; the rate of temperature rise in such a device is a measure of the heat flux it is receiving. Since the lateral dimension of the sheet was not given, the spatial resolution is not known. The flux was measured just as the cigarette, initially adapted to free burn conditions, was placed on a horizontal surface supporting the gage. The average result was 4.2 W/cm$^2$ with a standard deviation of 0.8 W/cm$^2$; the variation among commercial cigarettes was judged to be not significant.

Damant [4-3] also reported measurements of maximum and "average" heat fluxes for 4 commercial cigarettes. Unfortunately the technique of measurement was not described. The results for maximum flux were all quite low, about 0.9 W/cm$^2$. This is much lower than any value seen in this study; the reason for this is not known.

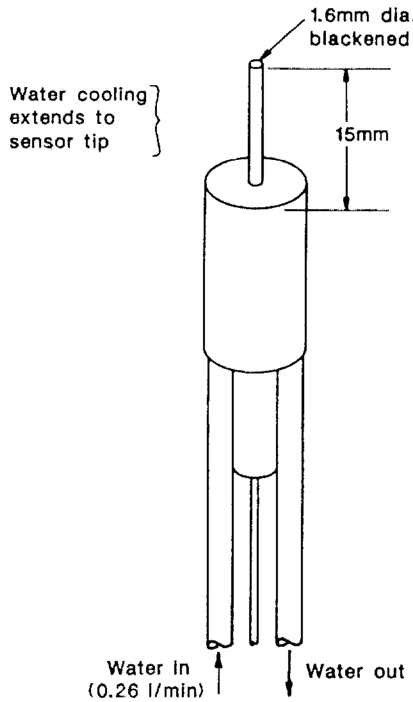
The total heat output (watts) of 4 experimental cigarettes was reported by Ihrig *et al.* [4-4], using a technique developed by Norman [4-5]. This technique, which provides a somewhat restricted free burn condition, essentially captures and measures a known fraction of the total heat output of a cigarette coal. The values obtained ranged from about 4 to 6 watts. Comparable numbers were obtained by Muramatsu [4-6] using measurements of the evolved CO, $CO_2$ and $H_2O$. A heat flux cannot be measured by these methods but one can estimate the approximate magnitude of the flux using the approximate coal area. The result (a few W/cm$^2$) is close to that of Behnke and to those of this study.

### Present Work

A miniaturized version of the technique used by Behnke was considered for this study. It was estimated that metal flakes 1 mm wide by 2 mm long having a 0.0025 cm thermocouple on the back would form about the smallest practical calorimeter; an array of such calorimeter flakes would be needed to obtain a flux distribution along one direction. There are several practical problems in the utilization of such calorimeter flakes that ultimately led to the rejection of their use in this work. Probably the most serious is the necessity of bringing the cigarette and flakes into very rapid contact in order to get a flux measurement. The cigarette must adapt to a substrate surface then quickly be moved to sit atop the flux gage array; any such move would destroy the adaptation of the cigarette coal to the substrate, since the coal surface responds rapidly to the local oxygen supply conditions.

A compromise between speed of measurement and spatial resolution led to the choice of a Medtherm Model 20321 Schmidt-Boelter flux gage (see Figure 4-1). This is a modified thermopile whose hot junctions form the 1.6 mm diameter sensor face and whose cold junctions are water-cooled. The front sensor surface is blackened to absorb radiation; of course, it also responds to any incoming conductive or convective heat flux, as well as any heat of

## Figure 4-1. Heat Flux Gage Used to Scan Flux Distribution Around Cigarette Coal

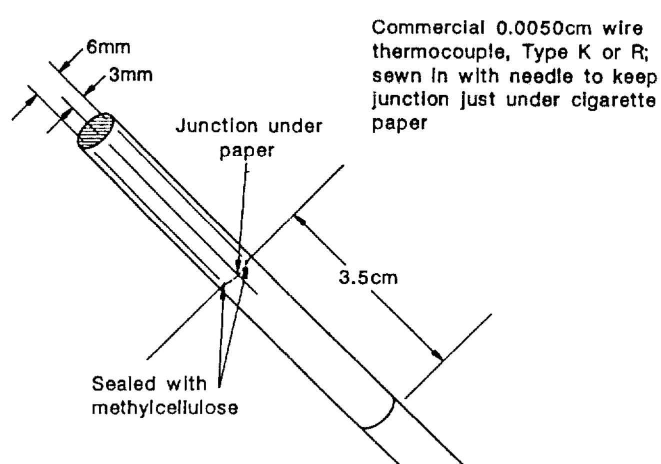



condensation of volatiles, such as water (this last factor should be a rather minor contributor to the heat flux). The gage response time is about 100 milliseconds. This gage can thus be scanned past the surface of the cigarette coal and provide a measure of the total flux profile along the direction of the scan. The spatial resolution is limited by the gage diameter. On the basis of Baker's temperature profiles [4-7], this does not appear to be a source of serious distortion of the flux profile; the tendency is to flatten the flux profile slightly and the peak flux is thus underestimated somewhat.[3] The maximum speed of scanning is limited by the gage response time. The scan speed was always the same at 2.7 mm/s. This means that it took 3 to 4 seconds to scan the central 10 mm portion of a flux distribution; this is 30 to 40 time constants so there should be minimal distortion of the distribution due to this cause.

There are two other aspects of the flux measurements, obtained in the above manner, which must be noted. First, it must be realized that the flux gage measures a "cold wall heat flux," i.e., during the process of measurement, the gage surface remains much cooler than the cigarette coal surface. In this regard it is the same as a substrate which has just come into contact with the coal. The low substrate or gage surface temperature enhances the conductive contribution to the heat flux and suppresses surface re-radiation. Because the gage is water cooled, its surface remains cool even if it stays in contact with the coal. The substrate surface, on the other hand, immediately begins to heat up as a consequence of contact with the coal. This causes the *net* rate of heat transfer to the substrate to decrease; conduction (across the gap between the coal surface and the substrate surface) decreases as the temperature difference decreases and re-radiation lessens the net radiative flux to the substrate. This decay of the net heat transfer flux is virtually impossible to calculate or to measure precisely; it is a very complex, three-dimensional, time-dependent problem. The inability to precisely determine this flux decay behavior presents a significant problem when one attempts to model the ignition process in the substrate given the initial incoming flux distribution from the coal; this issue is dealt with extensively in Section 5. It is less of a problem in comparative measurements of incident flux on the same substrate, as is the concern here, but it should be borne in mind.

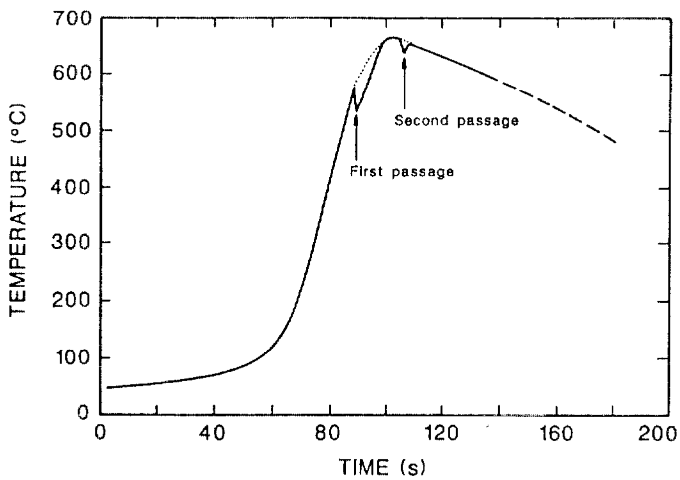
The second limitation on the flux measurements described here has to do with inevitable disturbances to the cigarette coal due to the proximity of the flux gage. This was alluded to above. Some measure of the disturbance can be obtained by placing a fine thermocouple just inside the periphery of the cigarette on the side past which the flux gage is scanned. Figure 4-2 shows the method of imbedding the thermocouple; this same technique was used throughout this work whenever peripheral temperatures were needed. Such

## Figure 4-2. Arrangement for Measuring Peripheral Temperature with a Thermocouple




*[3] This flattening is a function of the coal dimensions; it is greatest for cigarettes with the shortest coals and thus it introduces some systematic distortion into comparisons of peak fluxes among cigarettes. However, even for the cigarettes with the shortest coal lengths, the gage diameter is about one quarter of the width of the distribution at its half-peak height and the error (flux underestimate) appears to be of the order of 5% for this case.*

**Figure 4-3. Temperature-time on Periphery of Cigarette Showing Perturbation Due to Passage of Heat Flux Gage; Commercial Cigarette #6 in Free Burn**



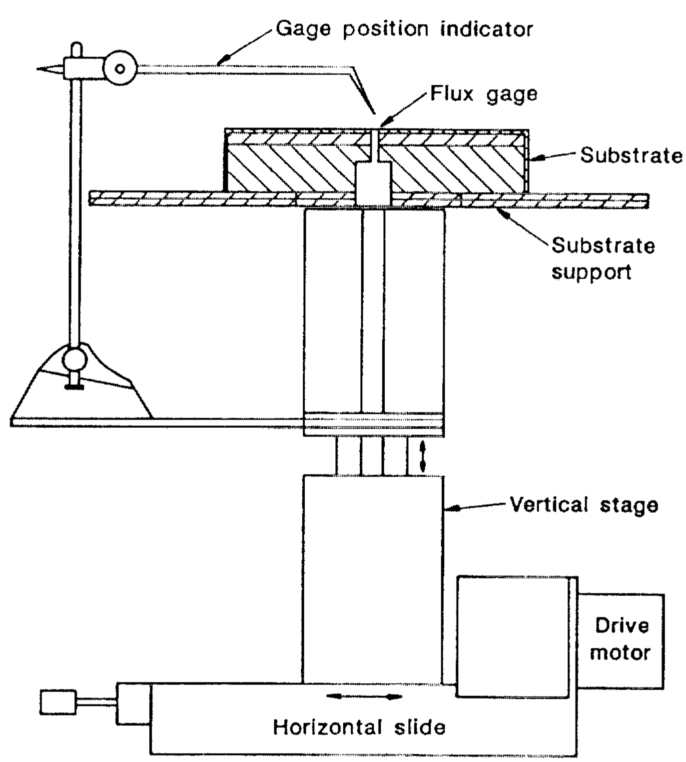

fine thermocouples (0.0050 cm) have been shown to provide accurate temperature measurements in a cigarette coal [4-18]. Figure 4-3 shows a typical result of temperature versus time obtained as the coal burns past the thermocouple. The two sudden dips in temperature near the top of the profile are due to two successive passages of the flux gage. Twelve repeats of this experiment on the same commercial cigarette (with two thermocouples per cigarette and two scans per thermocouple) gave an average temperature dip of 70°C. If the heat flux from the coal were totally conductive, this average temperature dip would imply that the peak gage reading is about 10% less than the value to be obtained from an undisturbed coal; if the heat flux were totally radiative, this dip would imply that the peak gage reading is about 27% low. The actual underestimate of the peak flux due to cooling by the flux gage is somewhere inbetween, probably near 15-20%. It is possible that this source of error varies somewhat with cigarette properties, but this has not been explored. It is worth noting that a metal flake used as a calorimeter, as discussed above, would extract heat from a cigarette coal at the same rate per unit area as does the flux gage used here and so does not provide a means for avoiding this source of error.

The apparatus for scanning the flux gage past the cigarette coal is illustrated in Figure 4-4. The gage is mounted on a vertical positioning stage that permits fine control of the position of the sensor surface relative to the bottom surface of the cigarette. This vertical stage is in turn mounted on top of a motor-driven slide which permits 3.5 cm of horizontal motion along one direction. The average scan speed, as noted above, is 2.7 mm/s. This varies slightly with position so, instead of using the average scan velocity and elapsed time to compute gage position during a scan, a position transducer is used. This is a linear resistor with a constant imposed voltage; a separate calibration is made to relate voltage and gage position.

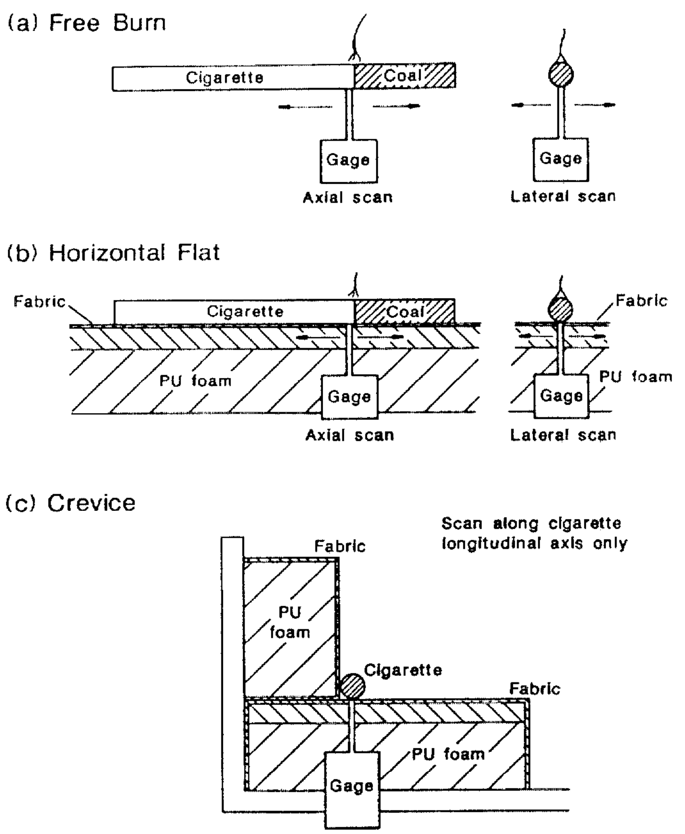
Flux scans were made in three different configurations illustrated in Figure 4-5. In all configurations the flux gage was positioned so that the sensor surface was in contact with the lower surface of the unburned cigarette over the length to be scanned. Coal shrinkage during burning typically caused a gap between the sensor surface and the hottest portion of the coal surface during the actual flux scans; this same gap exists between the coal surface and a substrate (see below).

Note that when a substrate was present it was necessary to insert the flux gage into it in order to get a measure of the flux from the coal at the interface between the cigarette and the substrate. This required a slit through the upper 1.27 cm of polyurethane foam and the fabric which was 1.6 mm wide (the width of the sensor face) and 6 cm long. The presence of the slit disturbs the interaction between the cigarette and the substrate. A series of thermocouple measurements of the temperature profile at the cigarette/fabric interface (thermocouple just inside the cigarette periphery with the junction on the bottom) gave a peak temperature there of 682 ± 18°C (average deviation) when there was no slit present; when a slit was present the result was 649 ± 14°C. These results were obtained with one cigarette type (FNLN-21, #110) on one non-igniting substrate (California fabric on polyurethane foam; fabric washed to prevent ignition; see below); the cigarette was allowed to adapt to smolder on the substrate surface for several

**Figure 4-4. Apparatus for Scanning Flux Gate Past Cigarette Coal**



## Figure 4-5. Flux Scan Configurations Used in this Study




minutes before the coal reached the thermocouple. The temperature decrease due to the slit means that the peak flux obtained in this manner is 5% to 13% lower than it would be if the slit was not present. This error range once again corresponds to either purely conductive or purely radiative heat transfer from the cigarette to the substrate and the most probable value is midway or about 9%. The fact that the temperature at the interface is lower in the presence of the slit suggests that the insulating effect of the substrate is more important than oxygen blockage in determining the local coal surface temperature, at least for this cigarette.

There is a further possible complication to incident flux measurements in which the flux gage is within the substrate: the hot substrate itself could contribute a significant portion of the flux seen by the gage. This factor was checked by a slight modification to the normal procedure with a flat horizontal substrate. A cigarette was placed on the substrate and given its first two sets of flux scans as usual; immediately after the last pass of the second set the cigarette was removed from the substrate and a final set of two scans was conducted within a few seconds. Any flux seen by the gage during this last set of scans must have come from the heated substrate; it was never more than 0.25 W/cm$^2$. This amounts to about 5% of the typical peak flux on a flat substrate; it is the first factor noted which increases, rather than decreases, the apparent heat flux.

In summary, an algebraic summation of the above error estimates for the heat flux measurements puts the net error (underestimate of the actual peak flux) at about 25 to 30% with the biggest contribution coming from the tendency for the flux gage to cool the periphery of the cigarette. This latter contribution is present for all configurations, as is that due to the finite diameter of the flux gage; when the flux gage is placed within the substrate, there are two further sources of error whose net contribution to the tendency of the gage to underestimate the peak flux is about 5%. The total net error of 25 to 30% should be largely independent of cigarette design and thus should not interfere with relative comparisons among the experimental cigarettes.

The axial scan for the various configurations in Figure 4-5 was easily implemented. The lateral scanning needed to build up a complete picture of the three-dimensional flux distribution was more problematical. The only natural position reference for these lateral scans is the paper burn line on the cigarette; this is a rather diffuse and erratically moving reference. What is needed is to make several lateral scans at known distances from the paper burn line as the coal burns past the gage scan line. Because of the behavior of the paper burn line, this cannot really be done reproducibly for successive cigarettes of the same or different type. Difficulties such as this, coupled with the fact that real differences in lateral flux distribution were difficult to demonstrate (see below), led to principal reliance on the axial scans for comparisons among cigarette types.

Each cigarette to be scanned was ignited by hand with a small flame (no suction) and allowed to burn freely in air for at least two minutes to yield a fully-developed coal. If the scans were to be done on a substrate, the cigarette was placed there after two minutes and given another two minutes (for a few fast burning cigarettes this was closer to one minute) to adapt to the new conditions of oxygen supply and heat loss before the first scan. Since, as explained above, the emphasis here is on behavior prior to any substrate ignition, a non-ignitable substrate was chosen to indefinitely extend the "pre-ignition" period in most tests. California fabric on 2045 polyurethane foam is not a very ignitable substrate in any event but fabric non-ignition was further assured by two successive soakings in distilled water (to remove catalytic alkali metals) after which it was air dried and ironed flat.

Axial flux scans were typically made at preset positions along the length of the burning cigarette. In most cases a set of scans was made as the paper burn line reached each of the following distances from the initial position of the lit end: 3.3, 4.2 and 5.1 cm. A set of scans means one scan with the flux gage moving in the same direction as the coal propagation and one scan in the opposite direction; thus a total of six scans was typically made on each cigarette. The coal is propagating during any given scan, of course, but this movement is typically less than 0.5 mm during a scan so it does not cause appreciable distortion of the flux distribution and the two scans in a set are not of significantly different width in spite of the difference in relative movement of gage and coal. Figure 4-6(a) shows a typical set of six scans from a cigarette with a moderate ignition tendency

**Figure 4-6a. Six Individual Scans on Same BEHC-21 Cigarette Sitting on Flat, Horizontal Substrate (Calif. Fabric/2045 Foam)**

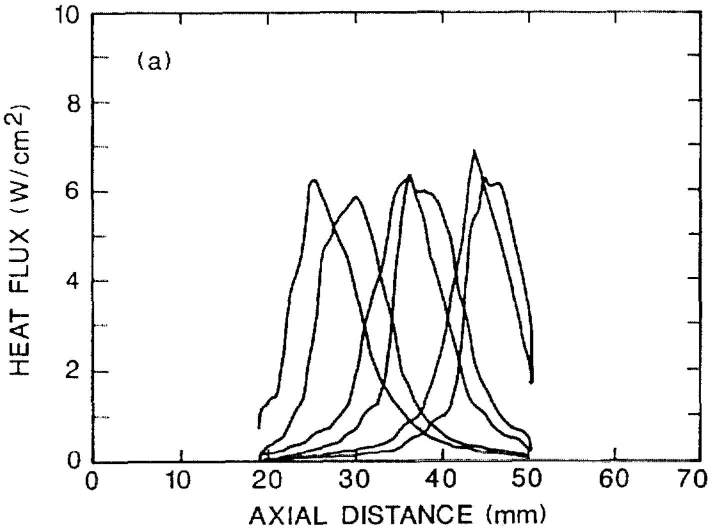
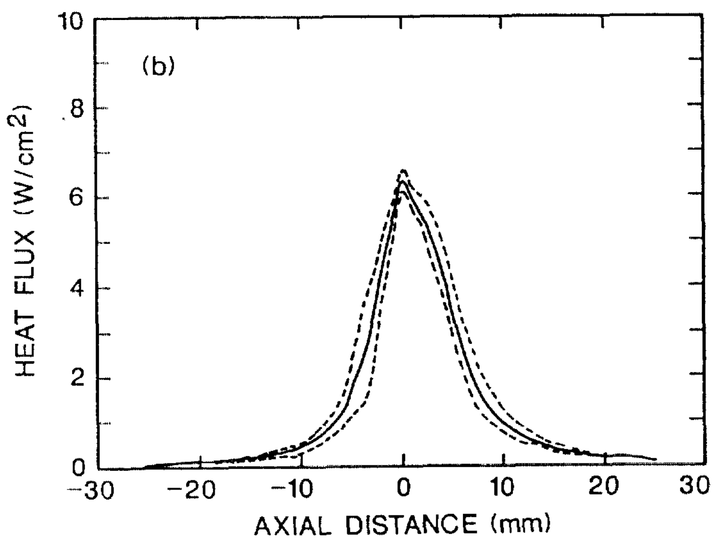



**Figure 4-6b. Averaged Results for Same Cigarette Data**




(BEHC-21, #107)[4]. These plots are produced by the computer which has simultaneously recorded the flux gage signal and the position transducer signal and converts them both *via* their respective calibrations. Note that, because of the limited scan distance available, the edges of the first and third scan sets are truncated. Occasionally individual cigarettes would show a consistent upward or downward trend in peak flux measured along the length of a cigarette. Since no cigarette type consistently showed such a trend, the six scans for each cigarette were superposed at their peak values and averaged. Figure 4-6(b) shows the average axial flux distribution thus obtained for one BEHC-21 cigarette. The dashed lines show the average deviation from the local average flux. It is curves such as that in Figure 4-6(b) which will be mainly used to compare cigarette types in the discussion below.

To reiterate, the 1.6 mm diameter flux gage used here gives a reasonably quantitative measure of the heat flux coming from a cigarette coal; the errors that exist in the measurements tend to yield peak flux values that are too low by about 25-30%. The measured flux is a "cold wall" value which is the same as is transferred to a substrate at the first instant of contact with a cigarette coal; this should not interfere with an inter-comparison of flux distributions among the experimental cigarettes nor with attempts to correlate these distributions with ignition propensity. Axial scans showed the greatest variation among cigarettes and will be used below in their inter-comparison.

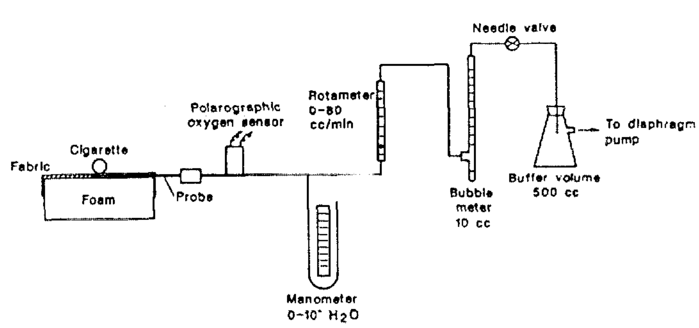
*[4]In constructing Figure 4-6(a), account was taken of the fact that the flux distribution is potentially asymmetric about the peak value and all of the scan data were plotted such that the ash side of the paper burn line is on the right.*

## Experimental Methods for Measuring Oxygen Depletion in the Substrate

The cigarette is an oxygen sink and so it imposes some oxygen depletion on its surroundings. This depletion is of particular interest in the hottest region of the substrate since this is where smolder initiation is likely to occur. If the oxygen level there is greatly reduced, it will tend to retard smolder initiation, making the requisite temperature for fabric ignition higher. If the reduction varies substantially among the experimental cigarettes, it will influence their relative ignition propensity.

A series of experiments was performed to determine the approximate oxygen level at the fabric/foam interface just below a burning cigarette coal. Figure 4-7 illustrates the sampling system used. The sampling probe is a 1.06 mm OD by 0.8 mm ID stainless steel tube inserted between the fabric and the polyurethane foam; a smaller diameter probe was tried but it was readily plugged by condensate. Care was taken to assure that the probe did not introduce an

**Figure 4-7. Apparatus for Sampling Oxygen Level Between Fabric and Foam**



external gas flow path along its own length that would pull in air from other than the coal region. The probe attaches to a short length of 0.16 mm OD tubing and then to a small volume (3.5 mm³) chamber glued on the end of the sensor from a Beckman model 778 polarographic oxygen analyzer. The goal is to minimize the volume between the sampling point and the analyzer so as to minimize the system response time in spite of very low flow rates. The flow was varied in a series of preliminary tests with one cigarette/substrate combination from 30 cm³/min. to 3 cm³/min.; the results were independent of flow rate from 8 down to 3 cm³/min, implying that disturbance to the coal by the sampling process was probably eliminated. A flow rate of 3 cm³/min. was used in all subsequent tests to minimize disturbance of the concentration field being measured. The system response time was about 12 seconds, determined largely by the analyzer response time, but lowering the sampling rate still further would have extended it undesirably. The remainder of the flow system shown in Figure 4-7 provides for flow control and measurement.

When a test was to be performed the flow system was stabilized and adjusted to the desired flow rate after the sampling probe was inserted under the fabric. A cigarette was lit with a small flame and allowed to smolder freely in air for 3 minutes. It was then placed on the horizontal surface of the substrate directly on top of the probe inlet position (previously marked on the fabric with a small ink dot). The coal was typically positioned such that the paper burn line was about 2 mm to the ash side of the probe position, i.e., the hottest part of the coal surface was placed directly over the probe position. In two tests this positioning was varied by a few millimeters but this did not appear to make a significant difference in the minimum oxygen level observed. Tests such as this were performed using three different cigarette types and three different fabrics, always on the same polyurethane foam type; these covered, in a limited manner, the range of cigarette and fabric characteristics seen in this study. A few tests were also done in which the cigarette was replaced by an electrically heated rod to determine the extent to which the observed oxygen depletion was due to causes other than the proximity of the cigarette coal. The rod heater was oriented vertically so that only its hot end (9.5 mm diameter) approached the substrate. The rod end was heated to a dull red glow and it was positioned about 2 mm above the horizontal fabric surface so that the size of the ignited region and its ignition delay time were about the same as in the case where a cigarette was the heat source. In all tests the oxygen level was recorded for about 4 minutes after heat source placement to ascertain its time evolution; the results are described below.

## Experimental Methods for Substrate Temperature Probing

In response to the imposition of a slowly moving, three-dimensional heat flux distribution (from the cigarette coal), the substrate heats up. The transient temperature field development is made quite complex by several factors— the nature of the thermal interaction with the cigarette, the two-layer structure of the substrate and the complex chemistry of the substrate materials. Attempts to predict this temperature field are discussed in Section 5. Here the emphasis is on efforts to measure some aspects of this field experimentally. The overall objective (Section 4 and 5) is to learn to what extent we understand the quantitative development of this field by comparing the measurements with the predictions.

A one-dimensional temperature distribution is easily measured; multi-dimensional fields are a much bigger challenge due to the need for a great deal more measurement points. Thermocouples are easy to use and would be the transducer of choice here were it not for the large number that would be required. The temperature field on the top surface of the substrate is potentially quite informative, especially since it is fabric ignition that initiates the substrate smolder process. The ready optical access to this surface opens the possibility of utilizing its emitted radiation as the measure of local temperature. This requires a sensor that can detect radiation in the middle to far infrared portion of the spectrum. An Inframetrics Model 525 scanning infrared radiometer was available and has been employed here for this purpose. This can be thought of as an infrared television which sees emitted infrared light rather than the usual reflected visible light. Radiation in the 8-12μ region is imaged onto an infrared detector that is cooled by liquid nitrogen. By means of a pair of oscillating mirrors, the particular small spot that the detector is looking at is swept at 30 frames per second in a rectangular raster scan pattern to form the field of view. The net result is that the IR camera gathers and displays information about objects in its field of view much like a television picture except that the number of horizontal lines is smaller (200 instead of 256). The instantaneous radiation intensity falling on the detector is proportional to the amount of radiation coming from the instantaneous object point in the field of view; the instantaneous detector output and the amplified signal from it that is displayed on a TV monitor are thus indicators of the brightness of the object point. If there is no significant 8-12μ radiation reflection from that object point (coming from other radiation sources) and if the object point is a blackbody emitter in this wavelength range, the intensity of the image of that point on the TV monitor is a measure of the temperature of the point. Both of these two conditions pose difficulties in the present application, which required special procedures, as discussed below.

Ideally one would be able to use this infrared camera to measure the temperature distribution on top of the substrate as a burning cigarette produces it. However, the cigarette is then the hottest object in the field of view. The cigarette coal emits intensely in the wavelength region of interest, more intensely than the substrate surface since it is hotter. Some of this coal radiation is reflected from the substrate surface since it is not perfectly black (though it may be close). The IR camera cannot distinguish between emitted and reflected radiation so it is unable to yield a correct temperature as long as the reflected radiation is present. Attempts to momentarily block this radiation by interposing a shield between the coal and the substrate surface (off to one side of the coal) were unsuccessful primarily because the inherent roughness of the fabric surface always allowed significant coal radiation leakage beneath the shield. An alternative technique was developed which called for rapid removal of the cigarette at the moment when a temperature measurement was to be made. Thus only one measurement could be made per cigarette/substrate burn test and that measurement was made after the cigarette had been allowed to heat the substrate for some pre-determined time such as two minutes; determination of the temperature distribution at some different time required another burn test with the same type of cigarette and substrate.

This technique entails further complications. As soon as the cigarette is removed from the substrate, the substrate begins to cool. The rate of cooling is variable, being generally higher where the local temperature is higher. Unfortunately it is quite high in an absolute sense everywhere of interest; the rates were in the range from 150 to 250°C/s. Because of video noise on each video frame, it is not practical to simply utilize just the frame at the instant of cigarette removal; instead one must average several frames to improve the signal-to-noise ratio. This requires an image processor[5] and the use of a video recorder to store the IR camera output prior to processing. At the same time one must compensate for the substrate cooling that is occurring over the frame averaging interval. Here averaging was done over two successive sets of four frames each, starting at the time of cigarette removal. An average temperature field was thus obtained for ⅛ s and ¼ s intervals after cigarette removal. At selected spatial points in these fields, a simple exponential decay function was fitted through the two known temperatures at that point and used to back extrapolate to time zero. In this manner the temperature field at time zero was estimated.

Surface emissivity in the 8-12μ region is less than unity for any real material. Thus it is necessary to measure it for the fabrics of interest and their chars which are formed due to heating. The technique chosen for this utilizes the IR camera. A sample of the material of interest is coated on one part of its surface with a known-emissivity material (e.g., carbon black or 3M Nextel Velvet Black paint); the remainder is uncoated. The material is then heated uniformly to some desired temperature in the range from 0 to 400°C. The IR camera then provides a means of quantitative comparison between the brightness of the uncoated surface and the coated surface; the brightness ratio allows calculation of the unknown surface emissivity at the given temperature. The values do tend to be rather high, between 0.9 and 1.0. Uniform heating of the fabric materials is difficult to achieve in some cases and this limits the accuracy of the emissivity determination.

There are other factors which limit the accuracy of the temperature obtained from the IR camera in the manner described above. There appears to be some error added to the signal in going through the video recorder in spite of automatic compensation for its gain control circuitry. The camera has a limited dynamic brightness range over which it can make quantitative measurements on images; it was necessary to use the least sensitive temperature range (500°C) in order to compress the very wide inherent brightness of the scene of interest into the dynamic range of the camera. Furthermore, there is something of a problem with the calibration between image brightness as seen by the IR camera and the actual source temperature apart from the emissivity issue. The camera operates by difference in its determination of an unknown temperature; it infers the temperature of the unknown by measuring the brightness difference between it and a source of known temperature and emissivity. This determination is more accurate if the known source (a black body in the work here) is close in temperature to the unknown. This same tendency affects the accuracy of the instrument calibration curves. The factory-supplied calibration curves are all obtained with a low reference source temperature (30°C). As a result, considerable effort was put into developing calibration curves for several higher reference source temperatures. However, the software program in the image processor would not accept these calibration curves due to limitations in its formulation. There was not sufficient time to rectify this problem and so the factory-supplied calibration was used. To compensate for this loss of accuracy, a fine thermocouple (0.0050 cm dia. chromel/alumel wire) was sewn into the fabric surface to provide an independent measure of temperature history at one point along the cigarette axis. The thermocouple junction location was marked for the IR camera by means of the heads of straight pins forming a 1 cm box pattern around it (away from the coal).

A final area of uncertainty with some of the fabrics of interest is the diffuseness of their surface. Particularly with a velvet fabric, the IR camera is likely to see radiation originating over some finite depth in the upper half millimeter or so; this is somewhat lessened by the fact that the camera views the surface at an angle of about 60° from the vertical. This would be unimportant if there were no temperature gradients over this depth but the insulating nature of velvet pile makes it probable that some gradient exists which is very difficult to assess. However, it is unlikely that this is a major source of error since the optical depth is rather small. In summary, the IR camera is a very useful device for discerning the sizes and shapes of the isotherms on the top surface of substrates heated by cigarettes; in this sense it is quite capable of revealing the relative differences in isotherm pattern induced by cigarettes of differing characteristics. However, in this application its quantitative accuracy is limited by the need to remove the cigarette before getting a reading. It is possible that the actual temperatures differ from those indicated by the camera by ± 25 to 40°C.

It should be apparent from all of the preceding discussion of experimental methods that there are substantial barriers to obtaining highly quantitative values for heat flux, temperature or oxygen concentration in this fragile, readily-disturbed system consisting of a cigarette interacting with a substrate. In all cases, however, it is possible to make reasonable estimates of the accuracy of the results. More importantly, it is clear that the results are sufficiently quantitative to permit

[5] *An IVS Model 210 image processing system was used for this purpose. It permits averaging up to 8 frames and provides for automatic conversion of pixel intensity to local temperature (given information on surface emissivity and possible reflected radiation as well as an instrument calibration).*

valid intercomparisons of measurements for the differing experimental cigarettes thus permitting the identification of those cigarette characteristics which influence ignition propensity.

# Results and Discussion

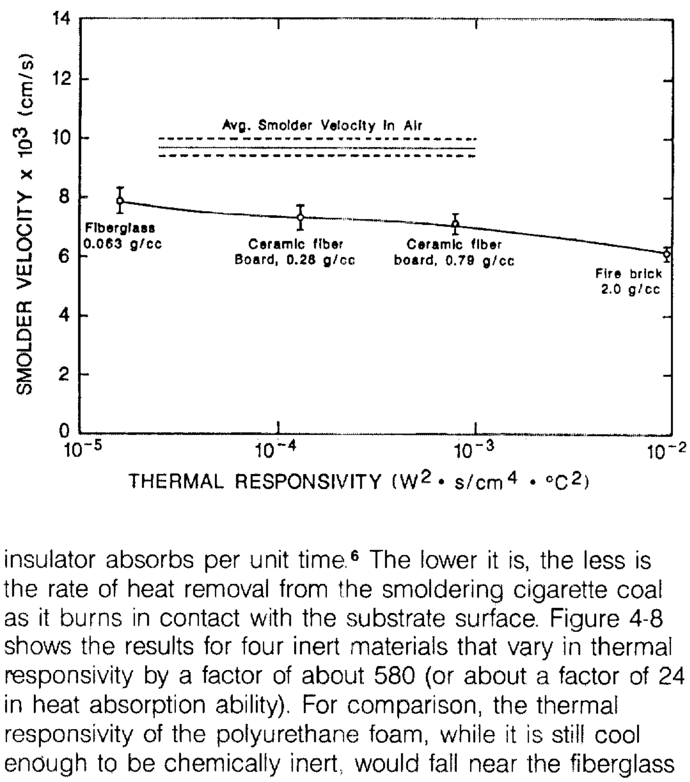
The first area of focus is the response of a cigarette to the proximity of a substrate and the way in which this affects the heat transfer from the various experimental cigarettes. As noted above, measurements were made in three configurations: on freely burning cigarettes in air, atop a flat substrate (usually California fabric on polyurethane foam) and in a 90° crevice formed by the same California fabric and foam. In seeking to understand how these flux measurements relate to ignition propensity, we have also examined cigarette coal dimensions, the gap between the cigarette coal and the substrate surface, and the depletion of oxygen in the fabric caused by the cigarette coal. In this same vein, a limited examination was made of the degree of unsteadiness in the coal surface temperature.

## Substrate Effect on Cigarette

Before the incident flux data are examined, it is of interest to look at what a substrate does to the cigarette coal. The presence of a substrate in contact with a burning cigarette could: (1) alter the heat losses from the coal and (2) alter the rate of oxygen supply relative to the free burn case. Either or both of these effects could thereby alter the incident flux that a substrate sees.

The conventional view of a steadily smoldering material is that it is burning at a rate dictated by the rate of oxygen supply [4-8]. Thus the principal effect one might expect on a cigarette sitting on a non-smoldering substrate is that it burns somewhat more slowly than in open air; the altered heat exchange with the surroundings would not be expected to have any appreciable effect, at least on the burning rate. Palmer [4-9] found such an insensitivity of burning rate to heat losses for dust layers smoldering on flat horizontal surfaces of asbestos and iron. This was tested here by placing a commercial cigarette (#C-6) on flat horizontal substrates of varied thermal "responsivity" or thermal "inertia". This parameter (the product of thermal conductivity, heat capacity and density) is the appropriate measure of transient thermal insulative capacity; the square root of thermal responsivity is a measure of the amount of heat an inert

**Figure 4-8. Burning Rate of Commercial Cigarette No. 6 on Several Inert Flat Horizontal Substrates of Varied Thermal Responsivity**



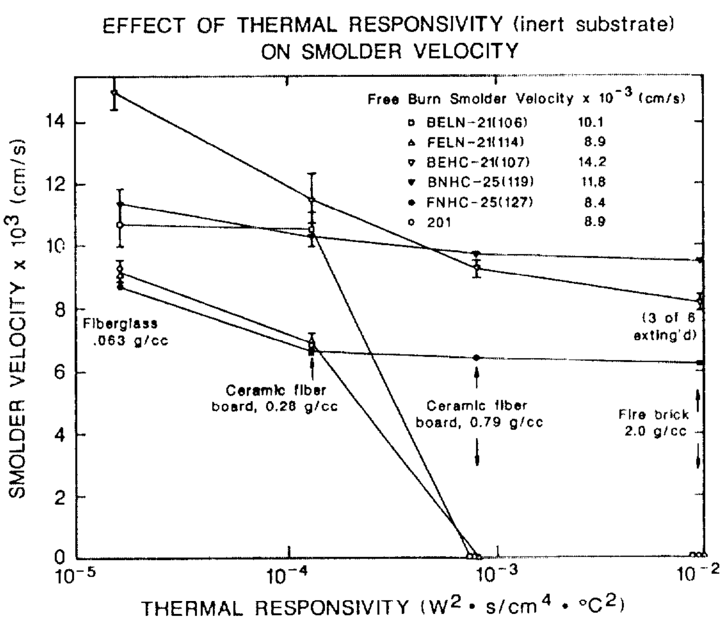

insulator absorbs per unit time.[6] The lower it is, the less is the rate of heat removal from the smoldering cigarette coal as it burns in contact with the substrate surface. Figure 4-8 shows the results for four inert materials that vary in thermal responsivity by a factor of about 580 (or about a factor of 24 in heat absorption ability). For comparison, the thermal responsivity of the polyurethane foam, while it is still cool enough to be chemically inert, would fall near the fiberglass in Figure 4-8; that of the fabric, while it remains inert, would fall near the lower density ceramic fiber board. It is apparent that, for this cigarette, the effect of increasing the heat loss rate to the substrate is only a very gradual decrease in smolder velocity and yet the smolder velocity on all of these

[6] *The heat content of a thermal wave in a material is proportional to the product of the average temperature in that wave, the density, the heat capacity and the wave thickness. This last variable is proportional to the square root of the product of thermal diffusivity and the time. One thus finds that the material properties measuring the heat content of the wave combine to yield the square root of the thermal responsivity.*

substrates is about 20% below that in air. This is consistent with the idea that oxygen blockage, not heat loss effects, dominates this 20% decrease in burn rate. Ultimately, of course, the heat losses, if sufficient relative to the rate of heat generation, will be overwhelming and their effect will be profound; the cigarette coal was severely distorted on the firebrick (the lower portion of the paper did not burn) and one in eight of the tests with this cigarette on this substrate yielded extinction.

Figure 4-9 illustrates the effect of heat losses on six of the experimental cigarettes used in this study. Three of these cigarettes have a rather weak propensity to ignite upholstery substrates as seen in the results of Section 3; these are BELN-21 (#106), FELN-21 (#114) and #201. One (BEHC-21, #107) has an intermediate ignition tendency and two (BNHC-25, #119 and FNHC-25, #127) have a strong ignition tendency. There are varying degrees of response to contact with the inert substrates which appear to correlate approximately with the ignition tendency; the cigarettes with the lowest ignition tendency are most susceptible to extinction due to substrate heat losses and conversely. One does not expect a perfect correlation here since extinction is probably dictated by an imbalance between rate of heat generation and rate of heat loss. The tendency to ignite upholstery is not solely dictated by the rate of heat generation in a cigarette, but for the cigarettes in this study, they may be closely enough tied together to produce a potentially useful correlation. Some exploration of a test method based on heat loss extinction is reported in Section 6. Four of the cigarettes (BEHC-21, #107; FELN-21, #114; #201; FNHC-25, #127) show a significant decrement in smolder velocity in going from the

## Figure 4-9. Burning Rate of Several Experimental Cigarettes on Inert, Flat, Horizontal Substrates of Varied Thermal Responsivity




fiberglass to the low density ceramic fiber board. Furthermore, their smolder velocity on the fiberglass is not less than in air as was the case in Figure 4-8 (in fact none of the cigarettes in Figure 4-9 is significantly slower on fiberglass than in free burn). Evidently any oxygen supply rate inhibition due to the fiberglass is made up for by what is probably a smaller heat loss in the presence of fiberglass. Some of the cigarettes (especially BEHC-21, #107)show an apparent sensitivity to heat losses over a wide range of substrate properties that does not seem to go along with the idea that oxygen supply rate is chiefly responsible for dictating smolder velocity. The smolder model of Moussa *et al.* [4-10], which includes predictions of extinction, implies that this kind of sensitivity to heat loss rate is possible over only a narrow range of temperatures and hence heat loss rates. It seems probable that what is happening here that is not included in such models is an interaction between heat losses and rate of oxygen supply. The heat losses may influence the area of the cigarette coal that is available for oxygen consumption and thus in turn affect smolder velocity; such an effect is quite apparent at least in the extreme cases where a cigarette is subject to a high heat loss rate, as when it was placed on a brick substrate. A similar point will arise later in relation to the role of the cigarette paper. The point is of interest because, as noted above, fabrics have thermal responsivities near the lower density ceramic fiber board. Evidently, in this range, some of the experimental cigarettes are vulnerable to both heat effects *and* oxygen blockage effects.

The issue of what a fabric/foam substrate does to a cigarette in contact with it is complicated by the fact that, above about 250-300°C, these substrate materials are not inert like those in Figures 4-8 and 4-9. The effect of a realistic substrate (after it is hot enough to begin to decompose) might not be to remove heat; its effect might be to add heat. Thermal analysis (DSC) of the California fabric in 9.3% oxygen (roughly the level present in the fabric when a cigarette is atop it; see below) yields an exothermicity of 950 cal/g of fabric for the pyrolysis step (preceding char oxidation). One can show that, from this degree of exothermicity and an estimate of the amount of fabric pyrolyzed by the cigarette coal, the cigarette heat release rate ought to be significantly supplemented (10-15%). However, this exothermicity result is for a heating rate of 5°C/min.; the heating rate that a fabric sees when it is placed in contact with a cigarette coal is closer to 200°C/min. The effect of this difference in heating rate on the net heat release from the fabric is indeterminate due to instrumentation limitations but it is likely to decrease the exothermicity somewhat since there is less time available for oxygen attack; such a decrease at lower heating rates has been seen for polyurethane foams which are also exothermic in their decomposition at very low heating rates [4-11]. In short, the net thermicity of the substrate's response to contact with a cigarette coal *prior to fabric ignition* cannot currently be determined directly. There are indirect indications from oxygen depletion measurements (below) that the pyrolysis heat release from the fabric prior to its ignition is probably minimal.

If the oxygen blockage effect by a substrate is the predominant influence on a cigarette coal, one expects that

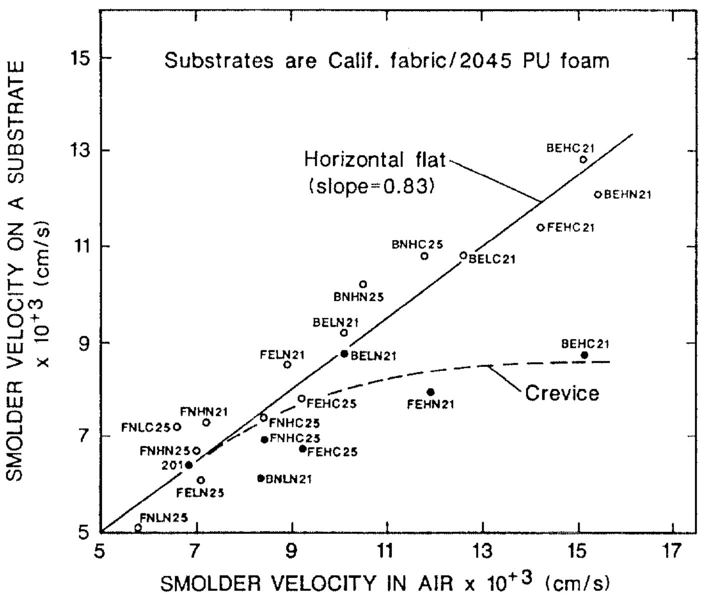



**Figure 4-10. Smolder Velocity on Two Substrate Configurations Versus Smolder Velocity in Free Burn**

all cigarettes will respond about equally to the same substrate, assuming the stoichiometry of char oxidation is about the same for all cigarettes. Figure 4-10 shows the decrease in smolder velocity on two different substrate configurations for several of the experimental cigarettes. The average decrease for cigarettes on the flat substrate ($\simeq$ 17%) is approximately the same as was seen above for the commercial cigarette on the inert substrates; the data for the crevice configuration are few, but they imply a decrease in smolder velocity about twice the fractional amount seen on the flat configuration. The scatter for both configurations is substantial and raises the question whether all the relevant factors are accounted for.

As the discussion of Figure 4-9 implied, the above argument about oxygen supply blockage is overly simple; it neglects the fact that the area for oxygen attack can change if the size of the coal changes with substrate contact. Six of the experimental cigarettes were examined in detail for this type of effect; coal lengths were measured about midway along the cigarette after extinction in a water bath. The results shown in Figure 4-11 are based on the average of three or more cigarettes; the average deviation was typically 5-10%. It is apparent that: (1) for any particular configuration there is a factor of two or more variation in the length of the coal; (2) the length of the coal generally increases as the cigarette comes in contact with configurations that increasingly block its oxygen supply (and perhaps significantly alter the local rate of heat loss). Both of these facts are pertinent to the substrate ignition tendency of these cigarettes; coal length directly affects the axial length of the incident flux distribution at the substrate surface.

A more detailed consideration of the issue of oxygen supply rate control on the cigarette burning rate leads to the following. Assume that the mass burning rate of tobacco is

**Figure 4-11a. Effect of Configuration on Smolder Velocity of Six Cigarettes: BELN-21(106), FEHN-21(116), FHNC-25(127), FEHC-25(131), 201, BNLN-21(102)**

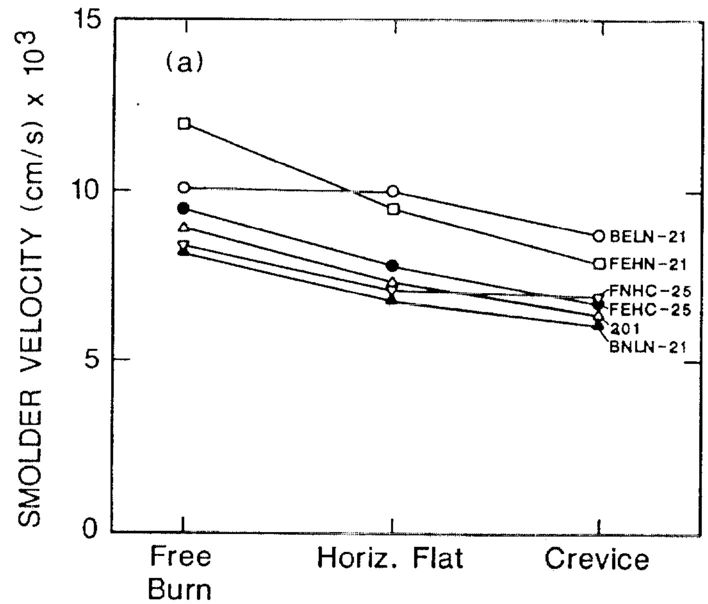
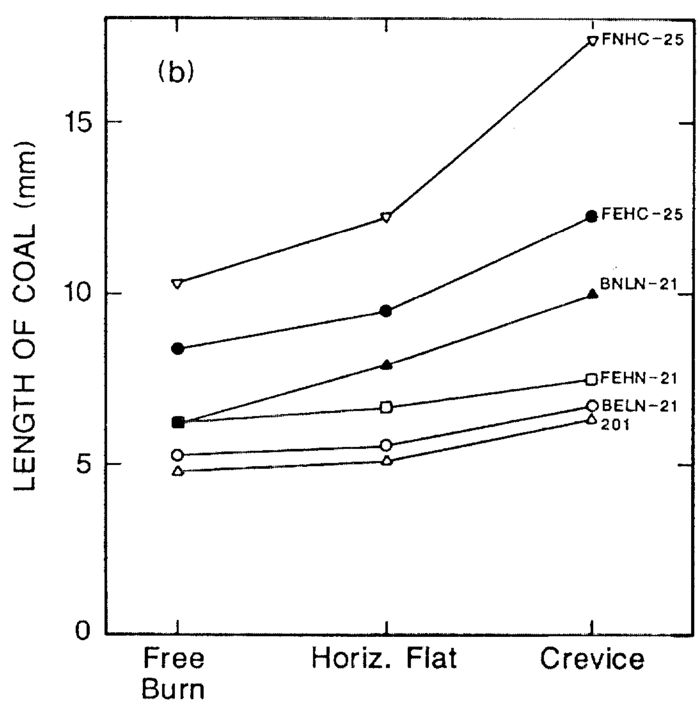



**Figure 4-11b. Effect of Configuration on Coal Length for the Same Six Cigarettes**



related to the rate of oxygen supply through a fixed stoichiometric coefficient:

$$m_{TOB} = \rho_{TB} v_S A_{CS} = (1/n_{OT}) k A_{COAL} Y_{OXA} \qquad (4\text{-}1)$$

where $m_{TOB}$ is the mass burning rate of the tobacco (g/sec.), $\rho_{TB}$ is the bulk density of the tobacco in the cigarette, $v_S$ is the smolder velocity of the cigarette (cm/sec.), $A_{CS}$ is the cross sectional area of the cigarette, $n_{OT}$ is the effective stoichiometric coefficient of the cigarette burning process, k is the mass transfer coefficient for oxygen transport across the boundary layer around the coal (and through the ash), $A_{COAL}$ is the area of the coal where oxygen is being consumed by char oxidation and $Y_{OXA}$ is the mass fraction of oxygen in the ambient atmosphere. Assuming further that the coal oxidation area can be approximated as a cone and substituting also for the cross sectional area in terms of diameter, one obtains:

$$\rho_{TB} v_S (\pi/4) d_C^2 = (1/n_{OT}) k (\pi/2) d_C s_C Y_{OXA} \qquad (4\text{-}2)$$

Here $d_C$ is the cigarette diameter and $s_C$ is the length of the slanted side of the coal ($s_C = (\ell_C^2+(d_C/2)^2)^{1/2}$; $\ell_C$ is the length of the coal). For a given configuration, the mass transfer coefficient, k, is essentially independent of cigarette diameter, having only a weak dependence that is masked by the small diameter range employed here. Assume also that $n_{OT}$ is constant for the two types of tobacco used here. Then, gathering constants on one side of the equation gives:

$$(\rho_{TB} v_S d_C / s_C) = (2/n_{OT}) k Y_{OXA} = \text{constant for a given configuration} \qquad (4\text{-}3)$$

This last relation provides a test of the assertion that oxygen supply rate dominates the behavior of the cigarettes in the configurations examined above. Figure 4-12 shows the result of replotting the data in Figure 4-11 in accord with the above relation; the average deviation in the points shown in Figure 4-12 is 10% or less. Clearly most of the cigarettes in most of the configurations conform to this relation. The decline in the value of the constant from left to right in Figure 4-12 is a measure of the change in the overall mass transfer coefficient with configuration. One cigarette, BELN-21 (#106), fails to conform when it is in contact with a substrate and the failure does not appear to be due to data scatter. BELN-21 is exceptional in that it has one of the lowest ignition tendencies among the experimental cigarettes; however, so does cigarette #201. The reason for the exceptional behavior of BELN-21 in Figure 4-12 is not apparent at present; perhaps it does not adjust to heat losses or oxygen supply restriction by altering its coal length in the same manner as the other cigarettes. The direction of its departure from the correlation is such that, on a

**Figure 4-12. Correlations of Oxygen Control Parameter (Eq. 4-3) with Burn Configuration; Same Cigarettes as Fig. 4-11**

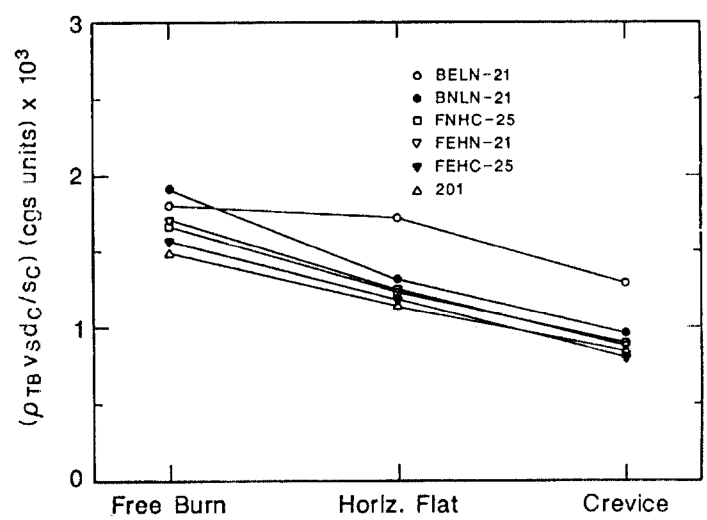



**Figure 4-13a. Coal Length in Free Burn Versus Tobacco Packing Density for Six Cigarettes (same as Fig. 4-11)**

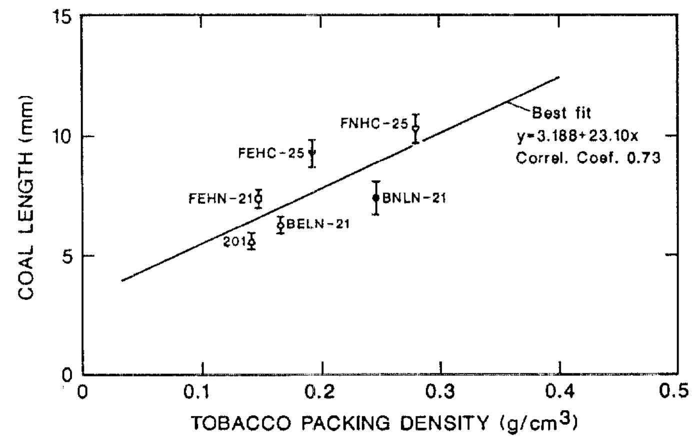
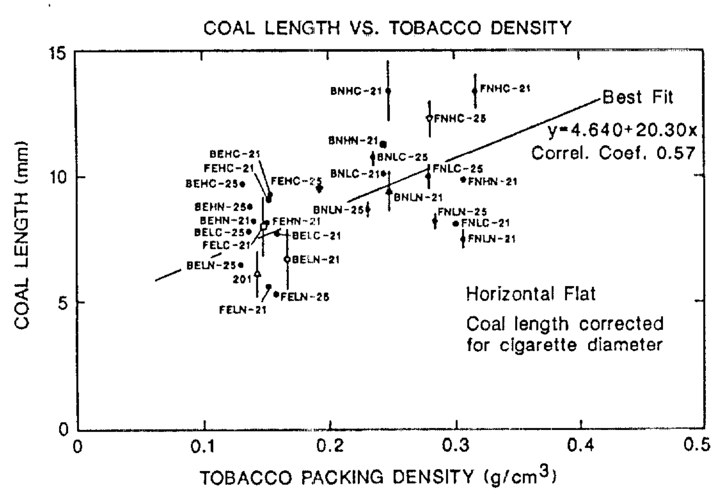
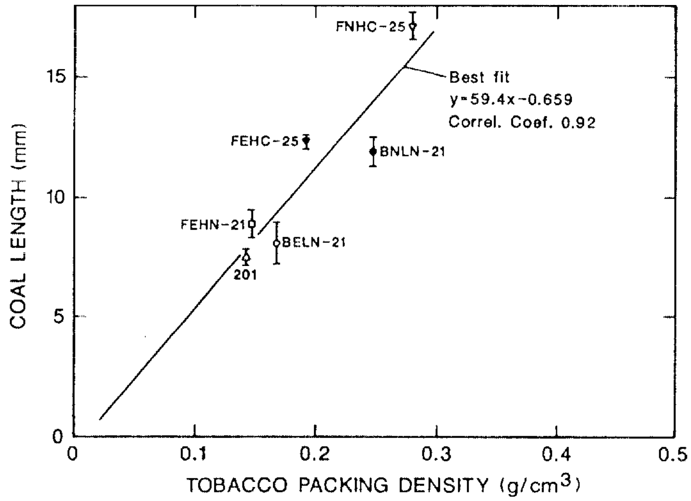



**Figure 4-13b. Coal Length on Horizontal Flat Substrate (Calif. Fabric/2045 PU Foam) Versus Tobacco Packing Density for Twenty-Eight Experimental Cigarettes**



## Figure 4-13c. Coal Length from Crevice Burn (Calif. Fabric/2045 PU Foam) Versus Tobacco Packing Density for Six Cigarettes (Same as Fig. 4-11)




substrate, either its smolder velocity is exceptionally high or its coal dimensions are exceptionally short.

Conformance to the above relation, while confirming that the interplay of coal dimensions and smolder velocity of most cigarettes is dominated by oxygen supply rate considerations, does not seem to fully explain how they show the considerable variability in coal length seen in Figure 4-11(b). The variation with configuration is explained as due to the need for increased coal area to compensate for the decrease in average rate of oxygen attack per unit area of coal (because of the partial blockage). However, this leaves the question as to what causes the coal length variability seen in Figure 4-11(b) among cigarettes in the same configuration. Variation in the packing density of the tobacco is the most obvious answer; one expects the coal to be longer if there is more tobacco per unit length to be consumed by the incoming oxygen flux. Figure 4-13 shows the correlation between coal length and tobacco packing density for the same three configurations discussed above. In all cases the coal length measured for a 21 mm circumference cigarette has been corrected upward by the ratio of diameters of the two sizes of cigarette; this was necessary to eliminate this source of bias and it assumes that the coal is conical in shape. Examination of Figure 4-13 leads to the conclusion that packing density is only one of the factors affecting coal length. All of the data in Figure 4-13 appear to be consistent with the idea that paper permeability is also a determinant of coal length; note the distinct tendency for cigarettes with high permeability paper to have a longer coal length. A possible tendency for citrate content also to increase coal length is more obscure.

The physical mechanism whereby paper characteristics affect coal length is not clear. It is well known that they affect the cigarette smolder velocity; higher citrate content and higher permeability both increase the static burning rate [4-12]. As will be seen, a longer coal does indeed go along with a higher mass burning rate. It could be argued that the higher permeability paper, in facilitating a greater oxygen supply rate to the coal region, enhances the mass burning rate in accord with Eq. 4-1. This glosses over what part of the coal receives this enhanced oxygen supply (apparently the pyrolysis zone) and it also offers no clue as to what the citrate in the paper does to enhance burn rate or coal length.

Paper HC (high permeability with citrate) does smolder faster by itself than the other three papers when burning upward and downward in air; see Table 4-1.[7] On the other hand, paper HN (high permeability without citrates) tends to self-extinguish in air. One can speculate that a faster paper might tend to advance more quickly along the cigarette, exposing a greater length of oxidizing char behind it, but this assigns the paper the role of a pilot in the cigarette smolder process. Such a role is dubious since the non-citrate papers want to self-extinguish and yet cigarettes

## Table 4-1. Upward Smolder Velocity, Paper only[a]

| Paper Type[b] | Smolder Velocity (cm/s) |
|---|---|
| LC | 0.21 ± 0.01 |
| LN | 0.20 ± 0.01 |
| HC | 0.29 ± 0.01 |
| HN | 0.22 ± 0.02 |

**Downward Smolder Velocity, paper only**

| Paper Type[b] | Smolder Velocity (cm/s) |
|---|---|
| LC | 0.14 ± 0.01 |
| HC | 0.18 ± 0.01 |

(a) Non-citrate papers self-extinguish; therefore, smolder velocity is from distance they did burn, others are from 4 cm length
(b) L indicates low permeability, 10 CORESTA; H is high permeability, 75 CORESTA; C indicates a citrate content of 0.8%; N indicates a lack of citrate

[7] *Note that the velocities in Table 4-1 are much faster than the smolder velocity of a cigarette. This does not mean that the papers could potentially smolder much faster than the tobacco when on a cigarette. It appears to reflect only the much better rate of oxygen supply that the paper receives when it is smoldering as a single flat sheet; placing several flat sheets together or forming a cylinder from a single sheet slows down the rate of paper smolder since either configuration reduces the rate of oxygen supply per unit area per unit mass of fuel.*

made with them smolder normally. Furthermore, inspection of extinguished and sectioned cigarettes suggests that the paper is relatively passive, pyrolyzing as the tobacco heats it; this may be only part of the story since low permeability, non-citrate papers appear to lag behind the tobacco char front. A paper that merely pyrolyzes at a lower temperature would lengthen the coal somewhat, but Baker's temperature profiles [4-7] imply that a paper would have to pyrolyze at 70°C less than normal in order to lengthen the coal by 1 mm. Thermal analyses of the papers used here (5°C/min., air) show practically no differences (3-5°C) between the pyrolysis peak temperatures for the high and low permeability papers and 25-30°C lowering of the pyrolysis peaks in the presence of citrates. These effects could be greater or lesser at the much higher heating rate seen by the paper during cigarette smolder (300-500°C/min.); this cannot be judged from the present information. Ohlemiller [4-13] has found indirect evidence that the leading edge of a two-dimensional smolder wave is sensitive to the oxidation kinetics of the material in this region and has argued that these kinetics affect the length of the exposed char oxidation zone. These conclusions were based on studies of a thick layer (10-11 cm) of a homogeneous material (wood fibers) but they should be pertinent here as well. Thermal analytical results on the cigarette papers used here are not definitive with regard to the question of whether the paper oxidation kinetics differ in the proper manner here to explain such effects. Differences exist as seen in the thermal analysis results for paper oxidation at 1 to 5°C/min. but their effect on cigarette behavior is not clear in the absence of a model that incorporates the paper as an active and distinct element of the smoldering cigarette. It is worth noting that low paper permeability alone can cause a cigarette to self-extinguish [4-14]; the mechanism for this is also unknown but it suggests that model studies of the role of the paper could prove very interesting.

In summary, it is apparent from the behavior of the experimental cigarettes on inert substrates that the substrate can cause both oxygen blockage and heat loss effects on the cigarette; the extent of the effect on the smolder velocity appears to correlate in some approximate way with ignition propensity. On upholstery substrates, the alterations to the smolder velocity and coal length for most cigarettes are consistent with the assertion that the overall mass burning rate is dictated by the overall oxygen supply rate. This can be consistent with the idea that heat effects also count, if they act by altering the coal area available for oxygen attack. The cigarette design factors which have the largest impact on the coal length (which is a measure of the area available for oxygen attack) are diameter, packing density (determined by tobacco expansion and the cut width of the shreds) and paper permeability. The mode of action of the last is not immediately apparent.

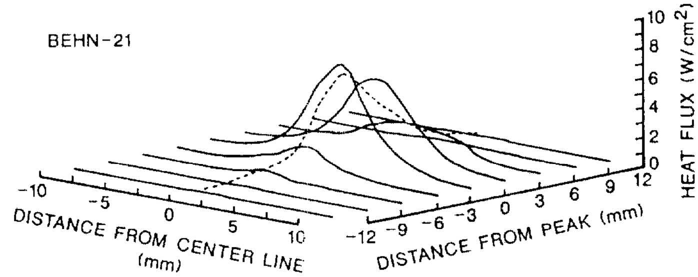
## Heat Flux Scans on Various Substrates

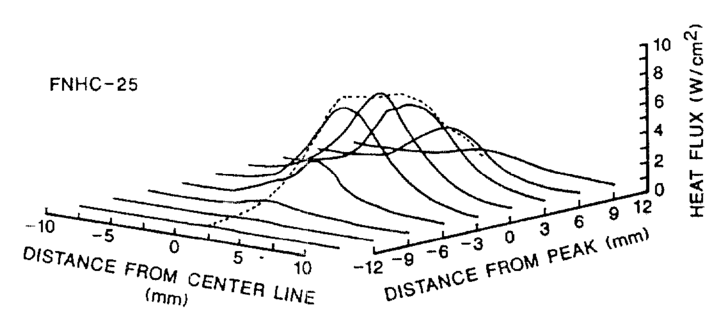
One result of the preceding discussion is that one expects the incident flux distribution seen on a substrate, even prior to substrate ignition, to be different from that from a cigarette in free burn. This is in fact the case as will be seen below for axial flux scans. It was also noted that there are substantial variations in coal length that should be reflected in the axial flux scans.

Recall that both axial and lateral flux scans are possible. If a complete set of both types of scan is taken on a given cigarette coal, the result is a picture of the three-dimensional flux distribution in the horizontal plane tangent to the bottom surface of the cigarette; Figure 4-14 shows two examples of this. In this figure the maximum of the axial scans has been placed at zero axial distance; the maximum is more likely at about +1 mm but it was not measured for these runs. Since the axial and lateral scans must be done on two different cigarettes, data scatter yields disagreement between them at several of their intersection points.

The two cigarettes in Figure 4-14 differ substantially in their smolder initiation tendency as measured by the total number of substrate ignitions reported in Section 3 (primary evaluation). BEHN-21 (#108) gave 7 out of a possible 20 ignitions; FNHC-25 (#127) gave 20 ignitions. One expects to see such differences reflected in the incident flux distributions. It is apparent that it is difficult to make quantitative comparisons between flux distributions with plots of this type, though it is

**Figure 4-14. Three-Dimensional Flux Distributions for Two Cigarettes in Free Burn. BEHN-21 (108) and FNHC-25 (127); Scans Along Horizontal Plane Tangent to Bottom Edge of Cigarette**



## Table 4-2. Lateral Scan at Burn Line

| Cigarette | Configuration | Average Peak Flux at Burn Line ($W/cm^2$) | Peak Width at Half of Maximum (mm) |
|---|---|---|---|
| BEHN-21 | AIR | 5.8 ± 1.0 | 5.5 ± 0.4 |
| BELC-21 | AIR | 6.1 ± 0.9 | 5.5 ± 0.6 |
| FNHC-25 | AIR | 6.0 ± 0.2 | 6.3 ± 0.3 |
| FNLN-25 | AIR | 7.1 ± 0.5 | 5.9 ± 0.6 |
| BELC-21 | FABRIC/FOAM | 5.5 ± 0.2 | 5.9 ± 0.6 |
| BELC-25 | FABRIC/FOAM | 5.0 ± 0.5 | 7.0 ± 0.4 |
| BELN-21 | FABRIC/FOAM | 5.3 ± 0.4 | 6.1 ± 0.4 |
| BELN-25 | FABRIC/FOAM | 5.2 ± 0.2 | 7.2 ± 0.4 |

The ± values are the average deviations

evident that they differ. Plots of this type are also not readily integrated numerically to obtain the total "volume" under the flux distribution surface though this is of interest, as will be seen below.

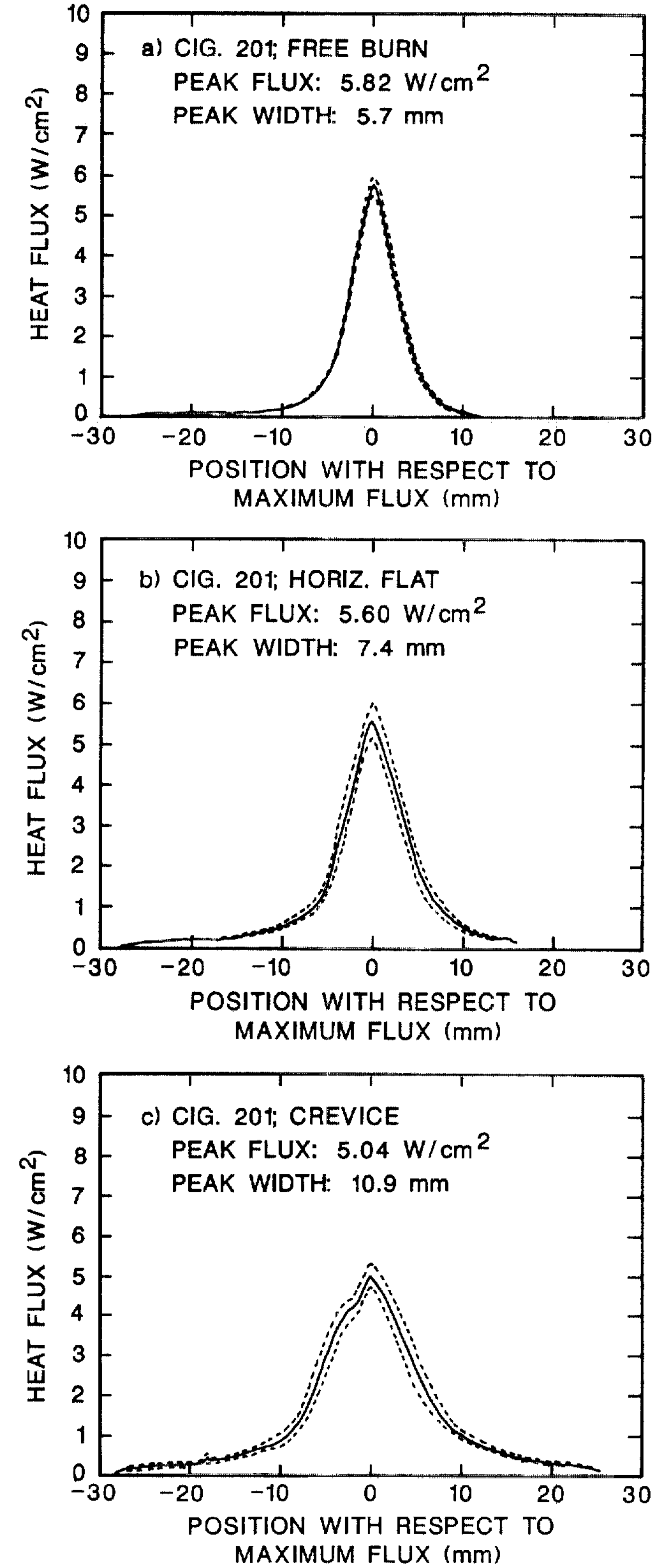
Lateral scans were made on several cigarettes, four in free burn and four on a flat substrate[8]; these were chosen to cover the range of ignition propensity. The paper burn line was the area examined most closely. Table 4-2 shows the results for the peak flux and the width of the flux distribution at the point where it has dropped to half of the maximum value; these values are averages for five to six cigarettes of each type with two scans past the burn line region per cigarette. The results for the first four cigarettes suggest that the peak width varies with cigarette diameter by about the same absolute amount as the diameter itself varies. There is some indication (perhaps not statistically significant) that peak width is somewhat wider on a substrate than in free burn (see BELC-21, #105); schlieren photos of the thermal boundary layer around the cigarette show that the presence of the substrate thickens it and this could broaden the flux distribution. The differences are rather small in both cases and do not justify the considerably increased effort required to obtain lateral scan profiles for all of the cigarettes examined in this study. In view of this discussion, the principal basis for comparing differing cigarette types here will be their axial flux scans.

Axial flux scans in three different configurations (free burn, flat horizontal surface and crevice) were made on four cigarettes[9] that span the spectrum of ignition propensity (as

[8] *Recall that the substrates have been rendered non-ignitable by washing any alkali metal ions out of the fabric; thus all results on substrates apply to pre-ignition conditions.*

[9] *Axial heat flux scans were made on a substantial number of other cigarettes in the experimental series, in both free burn and on a horizontal flat substrate (California fabric/2045 polyurethane foam). Copies of these are available for review at the National Bureau of Standards.*

## Figure 4-15. Axial Flux Scans of Cigarette 201 in Three Configurations; Dashed Lines are ± Average Deviation; Substrates are Calif. Fabric/2045 PU Foam



reported in Section 3) ; the averaged results are shown in Figures 4-15, 4-16, 4-17 and 4-18. The cigarettes in the first two figures (4-15, 4-16) have a minimal ignition propensity; that in Figure 4-17 has a moderate ignition propensity and that in Figure 4-18 has a strong ignition propensity. Two trends are evident with all four cigarettes as a function of configuration: (1) the flux distribution gets broader as one goes from free burn to the crevice configuration; (2) the peak flux gets lower or stays constant with the same change in configuration. These trends are qualitatively consistent with the cigarette temperature measurements of Salig, who subjected his cigarettes to more extreme oxygen blockage [4-1]. The first trend follows from the coal length data in Figure 4-11(b); recall that the coal gets longer because the substrate partially inhibits the inflow of oxygen and this slows the rate of char oxidation per unit length of coal. This same effect also slows the rate of heat generation per unit of char length and this is a prime determinant of the local surface temperature on the coal; it is the coal surface temperature which drives the heat flux incident from the coal on the substrate. However, the second major factor in determining the local temperature is the net rate of heat loss from the coal surface which is not so readily assessed. Recall that the overall thermicity of the substrate prior to fabric ignition is not known. Obtaining sufficient surface thermocouple data on the various cigarettes to provide a definitive comparison of the temperature profiles (at the side toward the interface) as a function of configuration has proven to be quite difficult; surface thermocouples are very prone to move and thus disrupt the measurement when they reach the coal region. The limited data available on BELN-21 (#106) and FNHC-25 (#127) suggest that any change in peak surface temperature with configuration is not large.

Inspection of Figures 4-15 to 4-18 allows one to compare the flux scans in any of three configurations for cigarettes that vary substantially in their ignition propensity. The most striking thing one sees is the lack of great differences; BELN-21 (#106, Figure 4-16) caused one substrate ignition in the tests reported in Section 3 whereas FEHN-21 (#116, Figure 4-17) caused twelve ignitions. Only FNHC-25 (#127, Figure 4-18) looks very obviously different from the other three; it caused twenty ignitions. The first implication that this comparison suggests is that peak flux does not clearly emerge as a controlling factor in the differing ignition tendencies of these cigarettes. One would expect peak flux to be a clearly dominant factor if the fabric ignition process took place in a time that is short compared to the coal movement time and compared to the time scale for lateral spread of heat in the substrate; in fact, all of these times are comparable here.

If peak incident heat flux did clearly dominate, the number of smolder ignitions for a given type of substrate and configuration would, ideally, go abruptly from zero to maximum as the critical flux needed to achieve the ignition temperature[10] of the fabric was reached; various substrates or configurations would then produce a series of steps in the total number of ignitions achieved in all tests. Figure 4-19 shows a plot of the number of substrate ignitions (from Section 3, primary evaluation) versus the peak heat flux from nineteen of the experimental cigarettes. The experimental situation represented in this figure is not optimal. The ignition tests of Section 3 were performed on three different substrate material combinations. On the other hand, the flux measurements here were all made on a single type of substrate — California fabric on polyurethane foam; horizontal flat configuration (Figure 4-5(b)) — because it was not feasible to test all of the cigarettes on all of the substrates. To help assess the effects of these differences, cigarette FNHC-25 (#127) was examined on three different fabrics (each on top of 2045 polyurethane foam in a horizontal flat configuration). Table 4-3 shows the results which are somewhat ambiguous as to whether different fabrics induce statistically significantly different peak incident heat fluxes from a cigarette (as a result of fabric/cigarette interactions); there could be a 20% difference between the California fabric and the other two fabrics.[11] Such a difference, even if real, is comparable to the data scatter in Figure 4-19. The correlation with peak flux does not look any better if only the ignition data for the one substrate covered in the California fabric is included in a plot like that of Figure 4-19. Thus the experimental data are unable to reveal a clear correlation between peak heat flux

[10] *Measurements of fabric ignition temperature were made using a large area electric heater as a radiation source; the flux was such as to provide a 1 to 1½ min. ignition delay, comparable to a cigarette. The fabric was placed on top of the polyurethane foam used throughout this work. The heater was about 1 cm above the fabric so that the appearance of glowing in the fabric char could be noted. A fine chromel/alumel thermocouple (usually 0.0051 cm dia. but 0.0076 dia. was used for some tests) was sewn into the fabric, making sure that the junction was within a thread or yarn and that the lead wires were in good contact also. Defining the ignition temperature in this type of experiment is problematical; ideally one wants the fabric surface temperature at which the ignition process becomes irreversible, such that, if the external heat flux were suddenly removed, the fabric would just be able to continue to smolder. Determining this ideal ignition temperature is an order of magnitude more difficult that what was done here. Here if the thermocouple record showed a rather abrupt increase in its rate of signal rise, indicating that the fabric temperature was rapidly rising due to the char oxidation exotherm, the temperature at which the rate of rise reached 21°C/sec. was arbitrarily taken to be the ignition temperature; for one fabric, halving this rate criterion would have lowered the inferred ignition temperature by 12°C and doubling it would have raised the temperature by 30°C. Visible appearance of char glowing as an alternative ignition criterion proved to be substantially less reproducible, although it was the only useful criterion with Splendor fabric which did not exhibit an abrupt increase in its thermocouple signal. For other fabrics this glowing char criterion tended to give ignition temperatures that were 40 to 85°C higher than the rate of rise criterion. With these caveats in mind, the results were as follows: Splendor fabric (glow criterion) — 536 ± 15°C; the remainder used the rate of rise criterion: blue denim fabric — 456 ± 13°C; unwashed California fabric — 454 ± 15°C; washed California fabric — 430 ± 5°C; second batch of washed California fabric — 424 ± 6°C. The California fabrics never smoldered beyond the area heated by the igniter. Note that these ignition temperatures apply to a situation where the heated area was several square centimeters; for a smaller heated area, comparable to that heated by a cigarette coal, the effective ignition temperature could be somewhat higher. Small area ignition temperature measurements were attempted but they gave much worse data scatter.*

[11] *If the 20% variation in peak flux is real, this says only that the different fabrics vary somewhat in their oxygen blockage and heat sink effects on the coal of a cigarette. This does not imply that the fabric characteristics play an equal roll to the cigarette characteristics in determining the heat flux pattern produced by a given cigarette on a given substrate.*

**Figure 4-16. Axial Flux Scans of BELN-21(106) in Three Configurations; Dashed Lines are ± Average Deviations; Substrates are Calif. Fabric/2045 PU Foam**

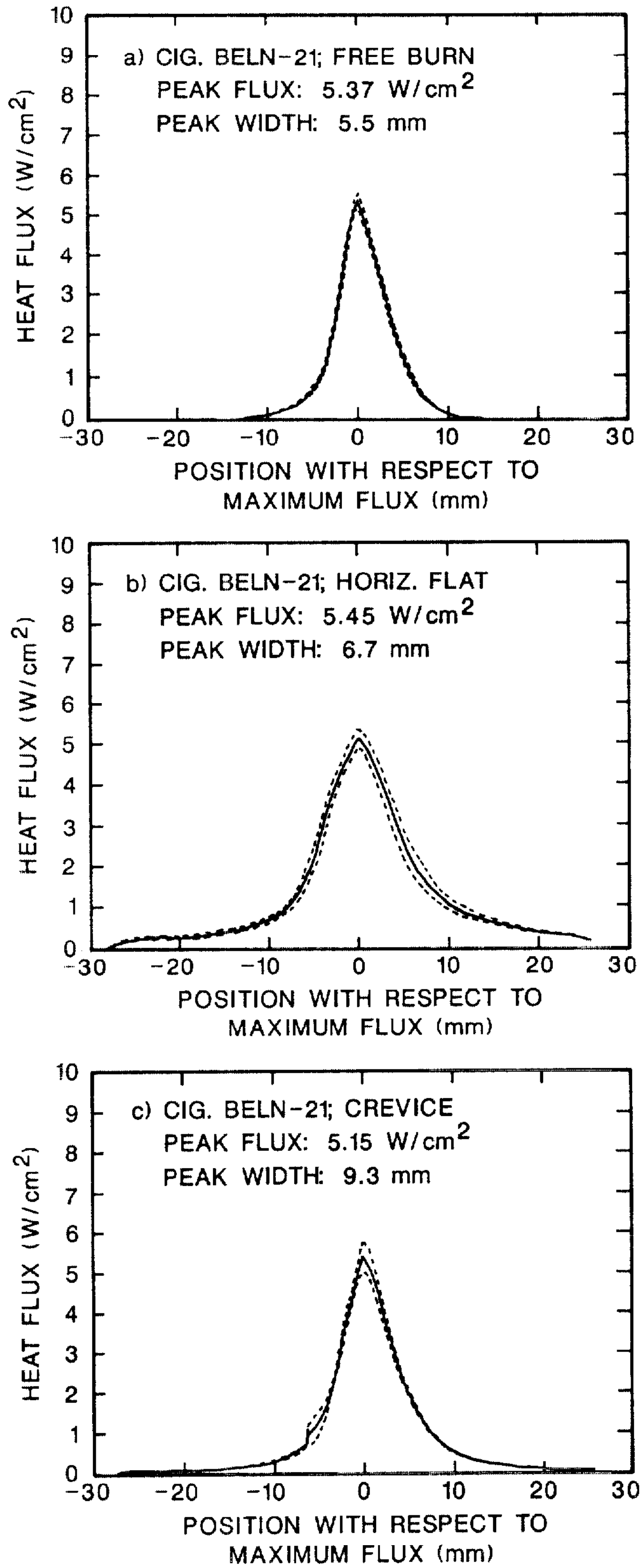



**Figure 4-17. Axial Flux Scans of Cigarette FEHN-21(116) in Three Configurations; Dashed Lines are ± Average Deviations; Substrates are Calif. Fabric/2045 PU Foam**

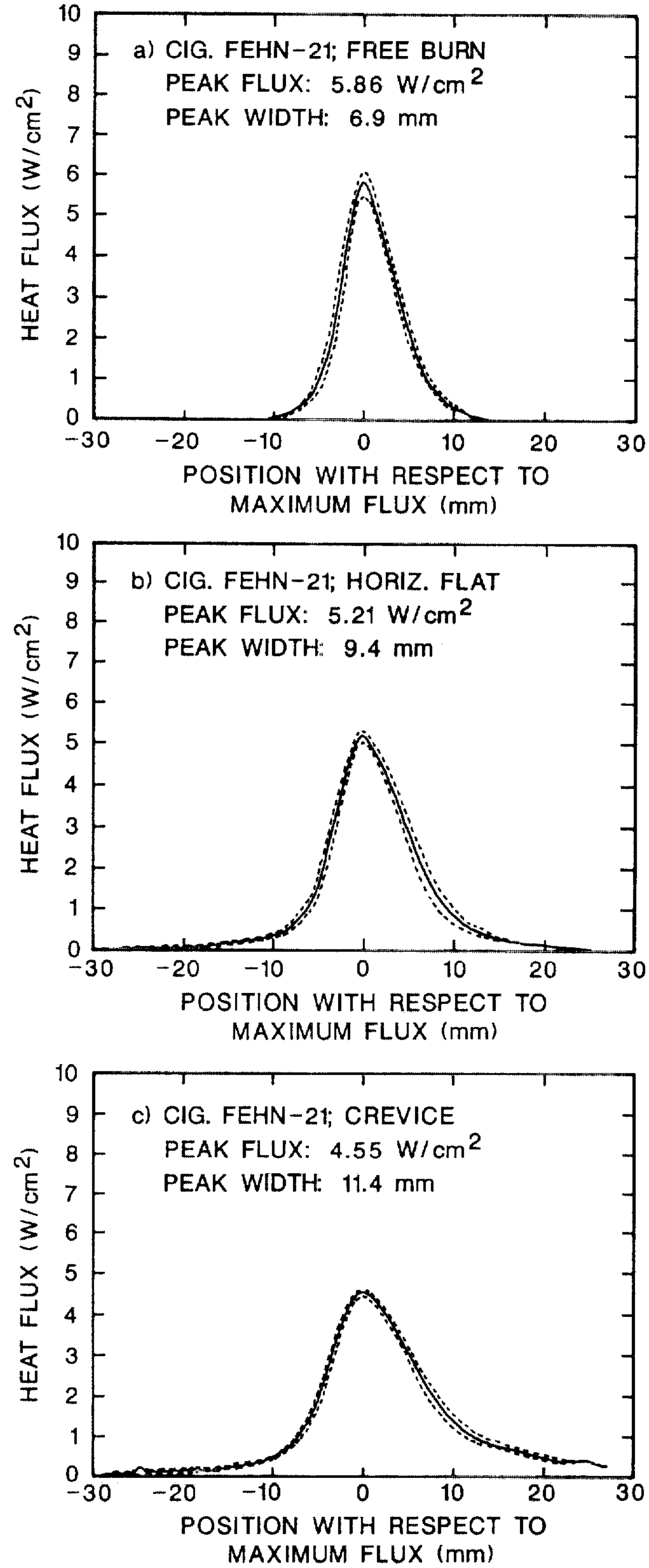


**Figure 4-18. Axial Flux Scans of Cigarette FNHC-25(127) in Three Configurations; Dashed Lines are ± Average Deviations; Substrates are Calif. Fabric/2045 PU Foam**

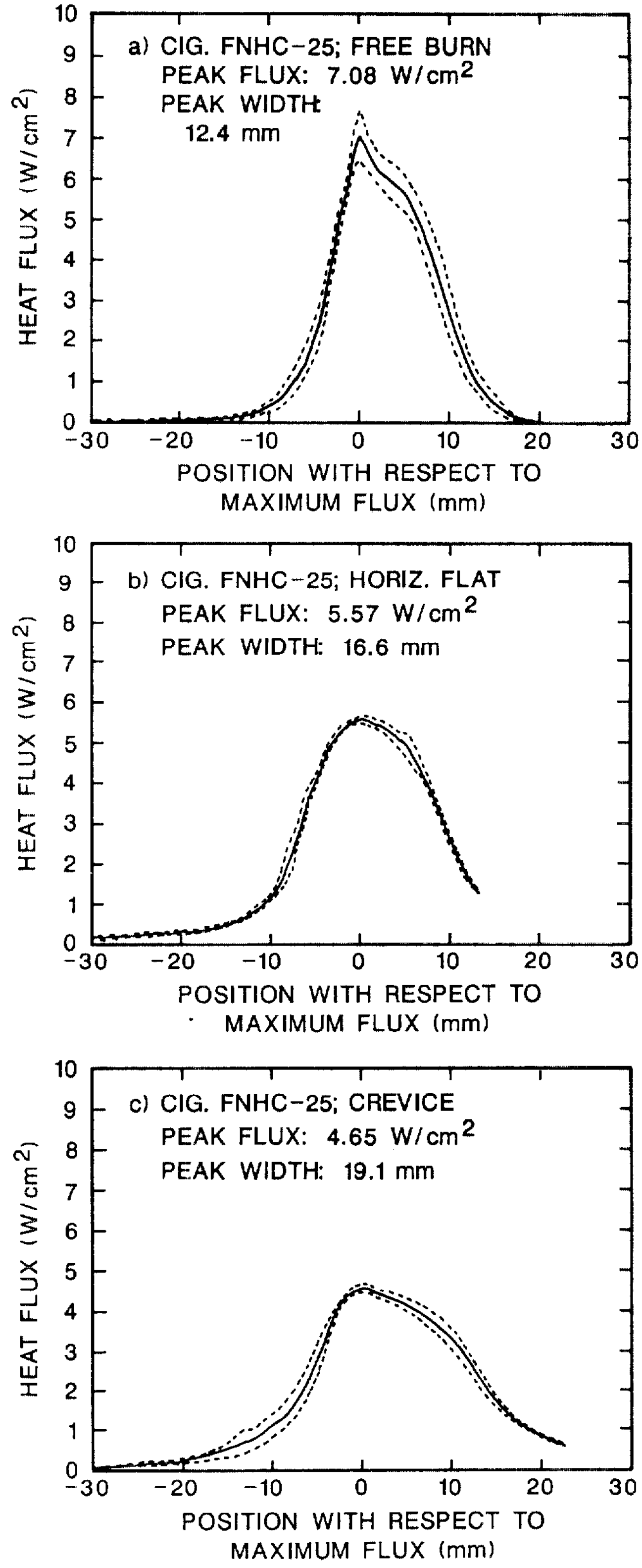
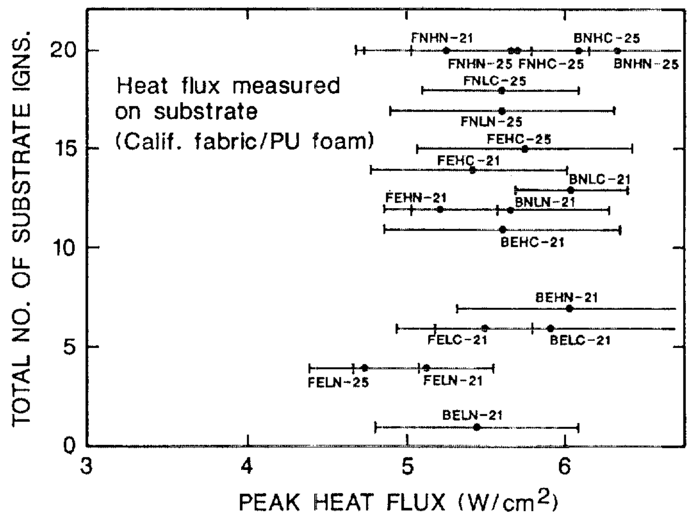



**Figure 4-19. Total Number of Substrate Ignitions (from Section 3) Versus Peak Heat Flux Measured with Each Cigarette on a Horizontal Flat Substrate Made from Calif. Fabric/2045 PU Foam**




and the ignition propensity of the experimental cigarettes.[12] It can be argued that Figure 4-19 contains some real trends; thus the average peak flux for cigarettes containing expanded and non-expanded tobacco is different as is the average peak flux for the two types of tobacco. Unfortunately the data scatter, coupled with the limited number of tests, makes it very risky to extract such trends.

The peak flux in all cases in Figure 4-19 is more than high enough, **if it alone were limiting,** to assure fabric ignition to smoldering. Such fluxes, if applied steadily over a sufficient area (significantly larger than the area of a cigarette coal), will quickly bring the fabric char to nearly the same temperature as the cigarette coal surface which will surely ignite it. Other factors must be preventing this in the case of some cigarettes; the speed of coal movement and the limited size of the coal are the most likely candidates.

[12] *The results in Section 5 indicate the peak flux should be the most important characteristic of the incident flux distribution in determining the maximum temperature achieved on a substrate, though it is not the only characteristic which affects this temperature. The results in Figure 4-19 do not clearly support such a principal role for peak flux because of the data scatter. In fact, there would seem to be some conflict with this idea in the results for low ignition propensity cigarettes such as BELN-21 (#106). This particular cigarette caused only one ignition in the primary evaluation of Section 3. Its average deviation in peak flux (Figure 4-19), coupled with the idea of peak flux dominance, would lead one to expect several ignitions, not just one. On the other hand, this cigarette has one of the shortest coal lengths (Figure 4-13(b)) and the raw heat flux data show a tendency for an inverse relation between peak flux and the axial width of the flux distribution; such a relation, particularly for a small coal length, would tend to allow radial heat conducting effects in the substrate to suppress ignition. Thus, resolving the results of Figure 4-19 with the results of Section 5 requires one to invoke a mix of flux distribution characteristics as being the determinants of ignition.*

**Table 4-3. Peak Heat Flux from FNHC-25 (#127) on Three Fabrics (over Polyurethane Foam)**

| Substrate | Peak Flux (W/cm²)[b] |
|---|---|
| Washed[a] California Fabric/2045 Foam | 5.6 ± 0.8 |
| Washed[a] Denim/2045 Foam | 4.9 ± 0.3 |
| Washed[a] Splendor/2045 Foam | 4.6 ± 0.5 |

(a) Fabrics were washed in distilled water to minimize their ignition tendency
(b) Average ± average deviation, four to seven tests per substrate

The narrow range of peak fluxes in Figure 4-19 evidently reflects, in large part, a narrow range of peak coal surface temperatures in spite of rather wide variations in the cigarette design parameters. Coal surface temperature is the primary driving variable that dictates the magnitude of the heat flux. As noted previously, coal surface temperature is determined by a balance between heat generation rate and heat loss rate; the former is in turn dictated by oxygen supply rate which is largely fixed by the constant configuration to which all the cigarettes in Figure 4-19 were subjected. Furthermore, radiation is a major fraction of the coal heat loss rate and it has a very strong temperature dependence, permitting small changes in temperature to compensate for larger changes in heat loss rate. Thus coal surface temperature is rather resistant to change and so is the peak incident flux from the coal surface to a substrate. Repeated temperature measurements were made on ten of the experimental cigarettes (four cigarettes of a given type with two thermocouples per cigarette) placed on a flat horizontal substrate consisting of California fabric over polyurethane foam; the thermocouples were in the cigarette periphery with the junction at the interface between the cigarette and the fabric. The average peak temperature ranged over about 50°C (635-688°C) but the average deviation was rather large (± 20°C to ± 50°C). The correlation with peak flux (Figure 4-20) is quite rough at best (if it can be said to exist at all); a result, in part, of the scatter in both variables.

There is a further factor which can alter the relation between peak temperature and peak heat flux incident on a substrate: the conductive (and convective) portion of the heat flux from the coal (as well as, to a lesser extent, the radiative portion) is sensitive to the distance between the coal surface and the substrate surface. This separation distance appears to vary somewhat with cigarette parameters; Figure 4-21 (a) and (b) show the results of repeated measurements of the gap between the bottom of a cigarette coal and the uncharred level of the fabric; the measurements were made with a cathetometer. Note that the full length gap takes time to develop but it then remains fairly constant. Comparison of Figure 4-21(a) and 4-21(b)

**Table 4-4. Effect of Gap Between Flux Gage and Coal on Peak Heat Flux Measured[a]**

| Cigarette | Additional Gap[b] (mm) | Peak Heat Flux (W/cm²)[c] |
|---|---|---|
| BELN-21 (#106) | 0 | 5.45 ± 0.5 |
| BELN-21 | 0.50 | 4.81 ± 0.3 |
| BELN-21 | 1.50 | 3.70 ± 0.2 |
| FNHC-25 (#127) | 0 | 5.57 ± 0.3 |
| FNHC-25 | 0.50 | 5.36 ± 0.2 |
| FNHC-25 | 1.50 | 4.03 ± 0.2 |

(a) Substrate is California fabric/2045 polyurethane foam
(b) As noted in the text and shown in Figure 4-21, some gap between the cigarette coal surface and the substrate surface normally exists; the additional gap here was produced by lowering the flux gage the indicated amount below the initial level of the substrate surface. The reduced flux at the 1.5 mm gap probably is due in part to shadowing of the flux gage surface by the edge of the fabric along the slit in which the flux gage resided.
(c) Average (± avg. deviation) of 3 to 4 cigarettes with six flux scans per cigarette

**Figure 4-20. Peak Coal Surface Temperature Versus Peak Incident Flux on a Substrate (Calif. Fabric/2045 Foam)**

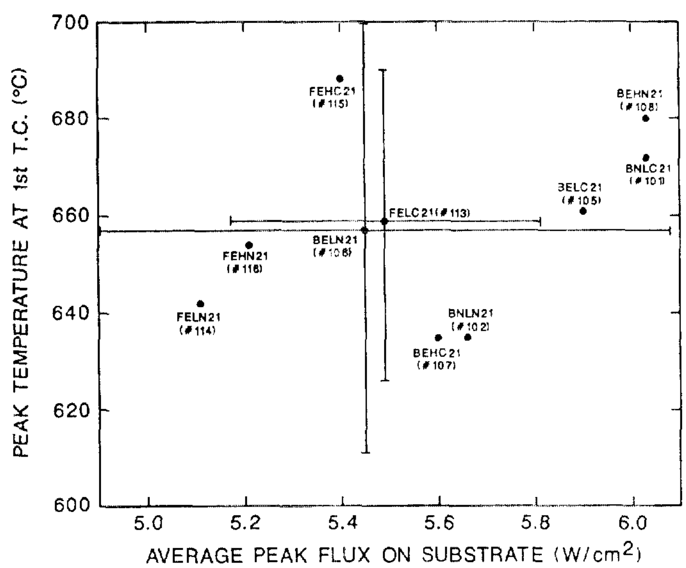
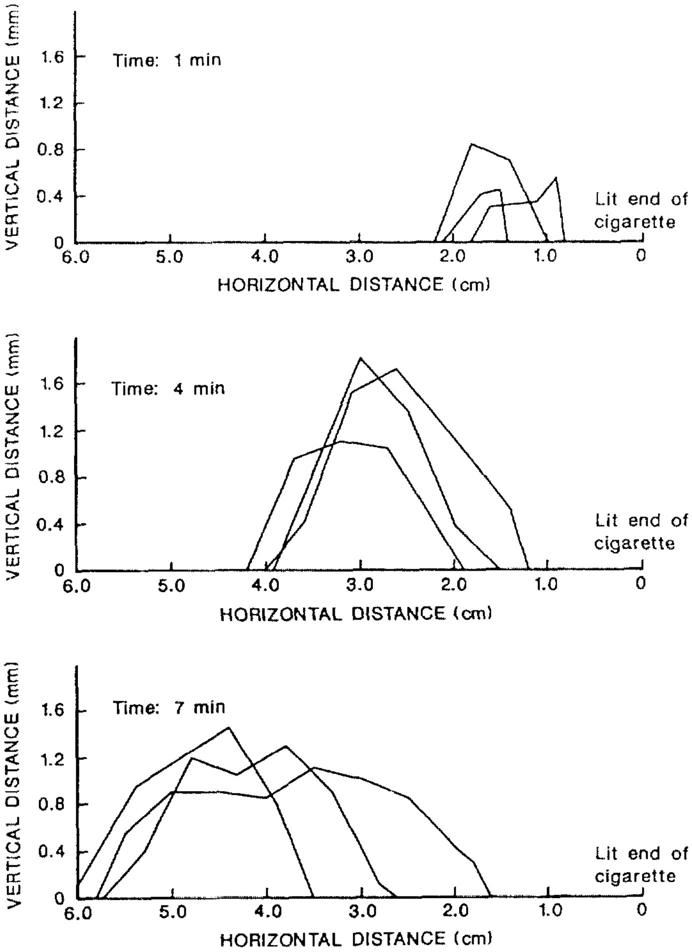


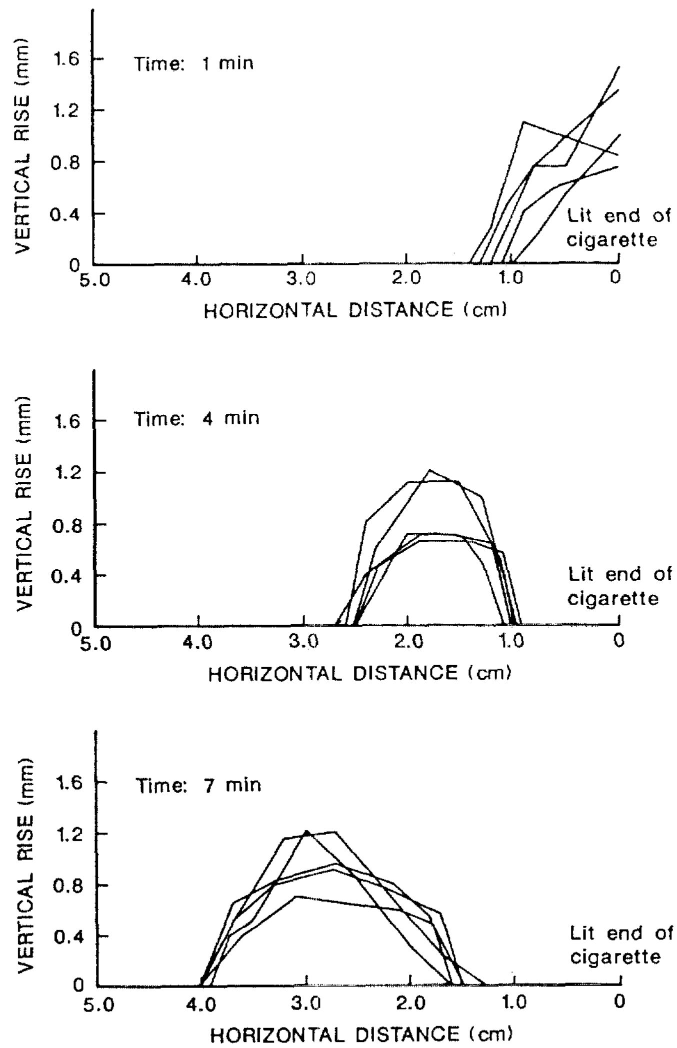
**Figure 4-21a. Measured Gap Between Coal Surface and Substrate as a Function of Burn Time on Substrate; Cigarette FEHC-21(115). Substrate is Calif. Fabric/2045 PU Foam. Individual Gap Profiles for Three Cigarettes.**




shows that, on average, there are significant differences between these two cigarettes; it suggests that the greater gap for FEHC-21 (#115) could be due to the expanded tobacco causing a greater shrinkage in the coal diameter. Diameter shrinkage alone is probably not the whole story behind the gap; increased heat loss to the substrate (as seen on the inert substrates of high thermal responsivity) increases the gap and this suggests a role for uneven rates of heating along the upper and lower surfaces of the cigarette. In any event, the role of this gap in altering the relation between peak incident heat flux and peak coal temperature is obscured by the fact that the peak temperature lies at a variable and rather imprecise distance from the paper burn line (which is at the left end of each measured profile in Figure 4-21); the distance is 1-2 mm typically. The overall gap undoubtedly does alter the flux profile seen on the substrate surface (as suggested by the results in Table 4-4 where an additional gap was introduced) and the variability of the gap, for a given cigarette type, probably contributes appreciably to the scatter seen in these profiles.

Return now to the issue of what aspect(s) of the incident heat flux profiles correlate(s) with the measured tendency of the experimental cigarettes to initiate smoldering in upholstery substrates. It was noted previously that the time scales for coal movement and for heat transfer through the substrate are comparable. There is a finite dwell time of the coal on any given point of the substrate surface; the total heat fed into a given point thus will decrease if the cigarette coal moves faster. If the rate of heat input at any given point on the substrate was invariant among the cigarettes (the peak, at least, is nearly invariant, as seen above), the time-integrated or total incident heat becomes potentially a significant measure of ignition tendency. Once again one expects

**Figure 4-21b. Measured Gap Between Coal Surface and Substrate as a Function of Burn Time on Substrate; Cigarette FNHC-25(127); Substrate is Calif. Fabric/2045 PU Foam; Individual Gap Profiles for Five Cigarettes**



that a series of cigarettes tested on differing substrates or in different configurations will produce a series of steps up from zero as each critical value of total heat input is reached.

A measure of the total heat input at a point can be obtained as follows. The passage of the coal over an arbitrary point on the substrate along the cigarette axis imposes a time-dependent flux at that point; the total heat input is the integral of that varying flux. Time and space along the direction of coal movement are related by the smolder velocity so that:

$$Q = \int_0^{\infty} F^*(t)\,dt = (1/v_S) \int_0^{\infty} F(x)\,dx \qquad (4\text{-}4)$$

Here Q is the desired integral that measures the total heat incident at a point, $F^*(t)$ is the time dependent flux seen by the point, $v_S$ is the smolder velocity on the substrate, and F(x) is the measured axial flux distribution. Of course, one does not really integrate to infinity but merely to a point where the flux is quite small. Note that this is a one-dimensional integral; it is the total incident heat per unit area but it applies only along the cigarette contact line with the substrate. Calculation of the total incident heat over the whole width of the coal as the coal moved past a region of interest would require integration over the distribution normal to the cigarette axis as well; as noted previously, this lateral distribution was not pursued here. The units of Q, as defined above, are Joules/cm². It should be noted that not all of this input heat is retained in the substrate; a good fraction of it is lost from the substrate as a result of heat transfer to the surroundings (by convection and radiation) as the substrate heats up.

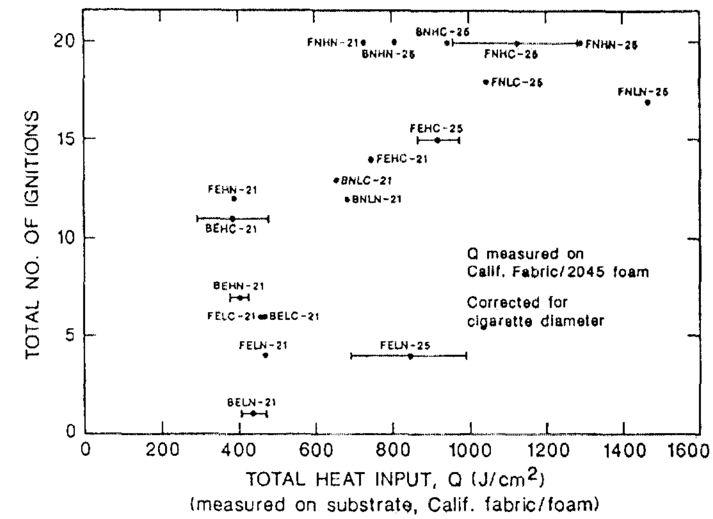
Note that this integral is derived from the incident heat flux measurements and is subject to the same sources of error. Once again the data were not obtained for each cigarette on

## Table 4-5. Effect of Fabric on Total Incident Heat From FNHC-25 (#127)

| Fabric[a] | Total Incident Heat (J/cm²)[b] |
|---|---|
| Unwashed Splendor | 855 ± 26 |
| Washed Splendor | 1117 ± 154 |
| Washed Denim | 1033 ± 70 |
| Washed California | 1129 ± 131 |

(a) Fabrics was always on top of 2045 polyurethane foam; horizontal flat configuration
(b) Average of five cigarettes ± average deviation

## Figure 4-22. Total Number of Substrate Ignitions Versus Total Heat Input Along Cigarette Axis; Heat Input Calculated from Flux Profiles on California Fabric/2045 PU Foam




each type of substrate used in Section 3 to measure ignition tendency; rather they were all obtained with the various cigarettes placed on flat, horizontal substrates consisting of California fabric on polyurethane foam. The results in Table 4-5 for one cigarette (FNHC-25, #127) imply that this is not a source of error; only the unwashed Splendor fabric, which was not used here, yielded an appreciably different total incident heat for this cigarette.

Figure 4-22 shows the correlation between Q, as obtained above, and the number of substrate ignitions from Section 3 (primary evaluation). Since the substrate does in fact respond not only to the axial flux distribution but also to the lateral flux distribution, a simple correction was applied to the values of Q to compensate for cigarette diameter differences; the Q values for 21 mm cigarettes were reduced by the ratio (21/25) = 0.84 before they were plotted. This correction does not appear to influence the interpretation of Figure 4-22. The results in Figure 4-22 do not have the simple upward stepped appearance from left to right that one expects from a perfect correlation. On the other hand, unlike Figure 4-19, there is at least a tendency for an increase in the number of substrate ignitions as the abscissa increases. It should be noted that not only is there scatter in the value of Q, there is also scatter in the number of ignitions and both of these factors will tend to obscure the ideal stepped appearance of such a plot. The flattening at the top is expected since the number of ignitions cannot exceed twenty. In any event, Q is clearly only a rather rough correlating variable for ignition tendency. The apparent degree of correlation is not improved by plotting the Q's against the number of ignitions on each separate type of substrate or configuration so this is not the source of the scatter in Figure 4-22. Total incident heat is simply not a wholly adequate measure of the effect of the cigarette on the substrates. Again, this is not entirely unexpected in light of the fact that lateral heat conduction in the substrate is occurring on a time scale comparable to that of coal movement over the top of the substrate; Q does not contain any direct measure of the lateral conduction effect.

A variable which does contain some measure of the impact of lateral heat conduction is the size of the "hot spot" that the cigarette imposes on the substrate; this is in turn proportional to the size of the cigarette coal. For the same heat flux, increasing the size of the heated area increases the peak temperature that can be achieved at the center of that area up to a limit achieved with one-dimensional heating; this limit should not be approached here [4-15]. Data on coal length and cigarette diameter are available. If it is assumed that the coal is conical and hence its cross-section as seen from the substrate is triangular, one can easily calculate a measure of the "hot spot" size as the area of this triangle. Of course, the actual shape of the "hot spot" on the substrate surface is more rounded than a triangle; the goal here is simply to obtain some roughly proportional measure of the actual spot size. If this variable (triangular area) provided a perfect correlation with ignition tendency, one would again expect a series of steps upward in the number of substrate ignitions as coal area is increased beyond some critical minimum. Figure 4-23 shows the correlation obtained here between projected coal area and the number of substrate ignitions from Section 3. Again the qualitative behavior is correct as it was for the correlation with total heat input; the scatter here is less than with that previous correlating variable. The scatter is still considerable indicating anywhere from one to sixteen substrate ignitions at the same coal area of 20 $mm^2$, for example; again, part of this scatter is in the number of ignitions. Clearly, coal area is not the whole story, but it appears to be a major contributor to ignition propensity. This suggests that three-dimensional heat conduction effects in the substrate are more dominant in this ignition problem than is either peak

**Figure 4-23. Total Number of Substrate Ignitions Versus Triangular Estimate of Planar Projected Coal Area; Cigarettes Burned on Calif. Fabric/2045 PU Foam**

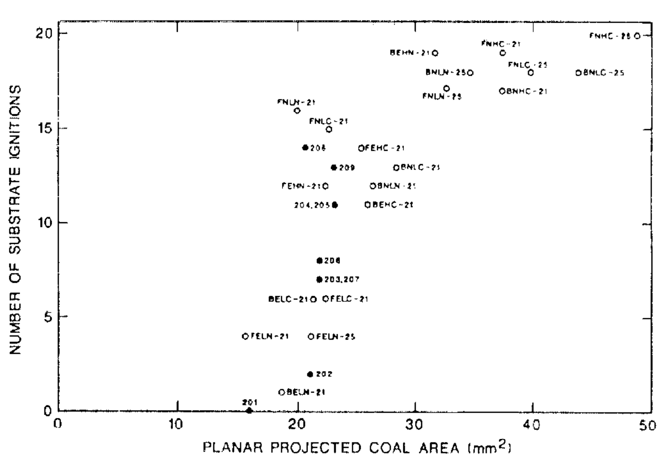



**Figure 4-24a. Correlation Between Mass Burning Rate of Batch One Experimental Cigarettes and Substrate Ignition Propensity Found in the Bench-Scale Tests of Section 3**

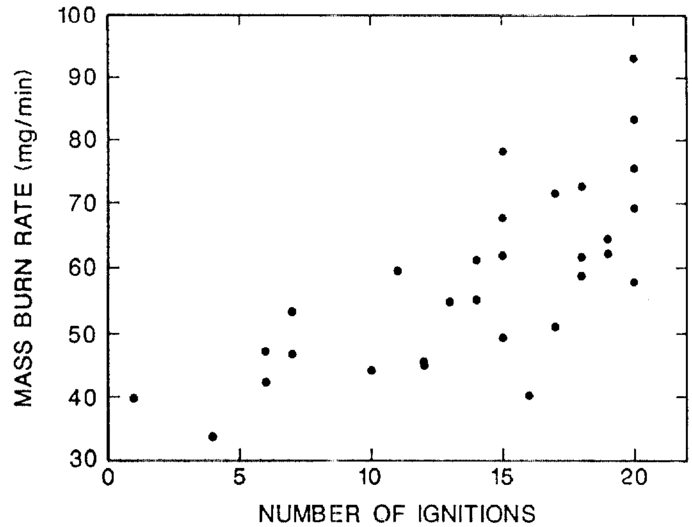
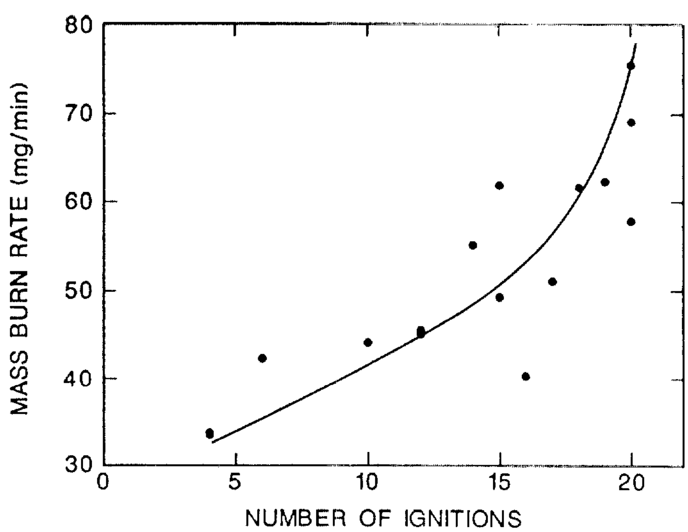


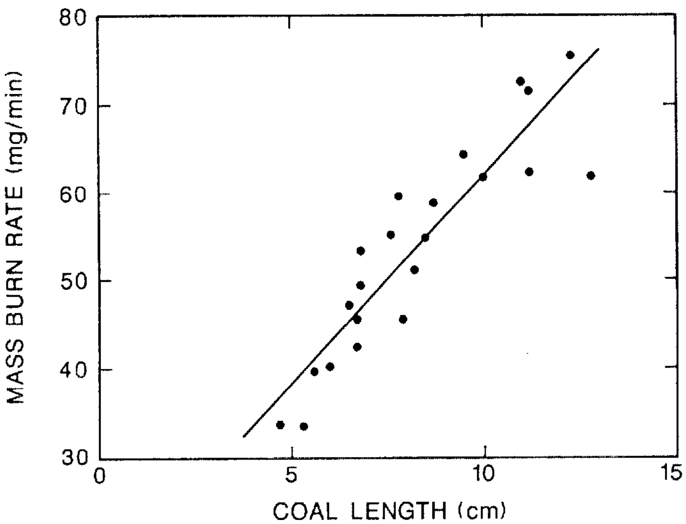

**Figure 4-24b. Same Correlation as Above but Restricted to Experimental Cigarettes Containing Flue-cured Tobacco Only; line is best fit second degree polynomial**




incident heat flux or total incident heat.[13] It is worth noting that Figure 4-23 suggests that a cigarette with a coal area less than 15 $mm^2$ would give a great improvement in ignition tendency.

[13] *Again, Section 5 assigns a greater potential role to peak heat flux than to coal dimensions. The evidently more dominant role of coal dimensions found here may reflect some correlation between coal size and incident heat flux characteristics not yet discerned.*

**Figure 4-25. Correlation Between Mass Burning Rate of Batch One Experimental Cigarettes and Coal Length (from cigarette burning on horizontal flat, California fabric over 2045 foam)**




It has been pointed out that a reasonable correlation exists between the number of ignitions and the mass burning rate of the first batch of experimental cigarettes [4-19]. Figure 4-24(a) shows such a plot for all of the cigarettes together; the correlation looks better if the two tobacco types are plotted separately as in Figure 4-24(b) showing flue-cured data only. Mass burning rate is a direct measure of the total rate of heat release from a cigarette. While one can reasonably expect that a greater rate of heat release could lead to increased heat transfer to a substrate (and, thus, a greater ignition propensity), in general there is not a sufficiently direct coupling between these two items to guarantee a one-to-one correspondence. Interestingly, for the cigarettes studied here, the coupling that appears to be behind the correlation in Figure 4-24 is a direct relation between mass burning rate and coal length; this is shown in Figure 4-25. Thus the mass burning rate correlation and the coal length correlation are related and the latter indicates the mechanism of increased heat transfer which helps cause a greater number of substrate ignitions. The existence of such a coupling between coal length and mass burning rate for cigarettes is implicit in Eq. 4-1 and also in the cigarette coal profile model of Gugan [4-20], though both are only approximate descriptions of the relation between oxygen supply rate and tobacco burning rate.

All of the preceding factors (peak flux, total heat input and "hot spot" size) count in determining the ignition propensity of cigarettes, though not equally for the particular set of cigarettes and substrates examined here. Furthermore, the details of the flux history imposed at each point as it moves over the substrate, count as well. The complexity of these dependencies is an inevitable consequence of the length and time scales involved in this problem. The single, simple measures of the flux characteristics considered here provide useful indications of directions in which to move to decrease ignition tendency but a definitive picture of the quantitative role of each variable requires detailed modeling of the ignition process of the type discussed in Section 5.

## Non-steadiness in the Coal Temperature

It is possible that the preceding picture of an ignition process dictated exclusively by the measured characteristics of the incident flux distribution from the cigarette is oversimplified. There may be other factors not accounted for there. Two possibilities come to mind; there may be others. The first has to do with the possible non-steady nature of the flux from some of the cigarettes. A cigarette resides on a substrate for several minutes, imposing a moving flux pattern during all of this time. The flux scans described above take only 3-4 seconds each; even with six scans per cigarette, the flux is measured only during a rather small fraction of the total ignition delay. It is possible that some cigarettes rather regularly and invariably produce, at least once during the burning of each such cigarette, short-lived increases in their rate of heat generation and, hence, heat flux due to inhomogeneities in paper or tobacco characteristics. Note that the focus here is not on random fluctuations which may or may not occur with any given cigarette. It could then be this occasional (but inevitable) higher heat flux, not the more-likely-measured average flux, that produces substrate ignition. The necessary characteristics of such deviations (duration, fractional deviation from the average and lateral extent) are a complex function of the time-average flux and the nature of the substrate. The simplest approach to assessing their possible importance is to look steadily at the entire coal of a cigarette during an extended period to determine whether significant temperature deviations from the average occur with some regularity over finite areas of the coal.

The line scan feature of the imaging infrared radiometer was used in a preliminary search for such fluctuating temperatures. This feature allows continuous monitoring of the emitted radiation along a fixed line which, in this case, was parallel to the longitudinal axis of the cigarette and included the full length of the coal. The peak emission level was monitored for ten continuous minutes of cigarette smolder atop a fabric/foam substrate (Calif. fabric/2045 foam); the cigarette/substrate interface could not be monitored but the scan line was on the side of the cigarette. Three different experimental cigarettes were examined in this manner (with three replicates of each); these were FNLC-21 (#109), FEHN-21 (#116) and FELN-25 (#130). These cigarettes were chosen because they gave widely differing numbers of substrate ignitions in spite of having essentially the same value of projected coal area (Figure 4-23). The results in all cases showed no short term emission (and thus temperature) fluctuations. There was in some cases a long term drift in the signal corresponding to temperature changes of about 40°C, but such slow changes would not have been missed in the normal axial heat flux scans. Thus this preliminary look for significant surface temperature fluctuations that might explain some of the scatter in the preceding correlations was negative. Time did not permit a more extensive examination of this question.

## Oxygen Depletion in the Fabric

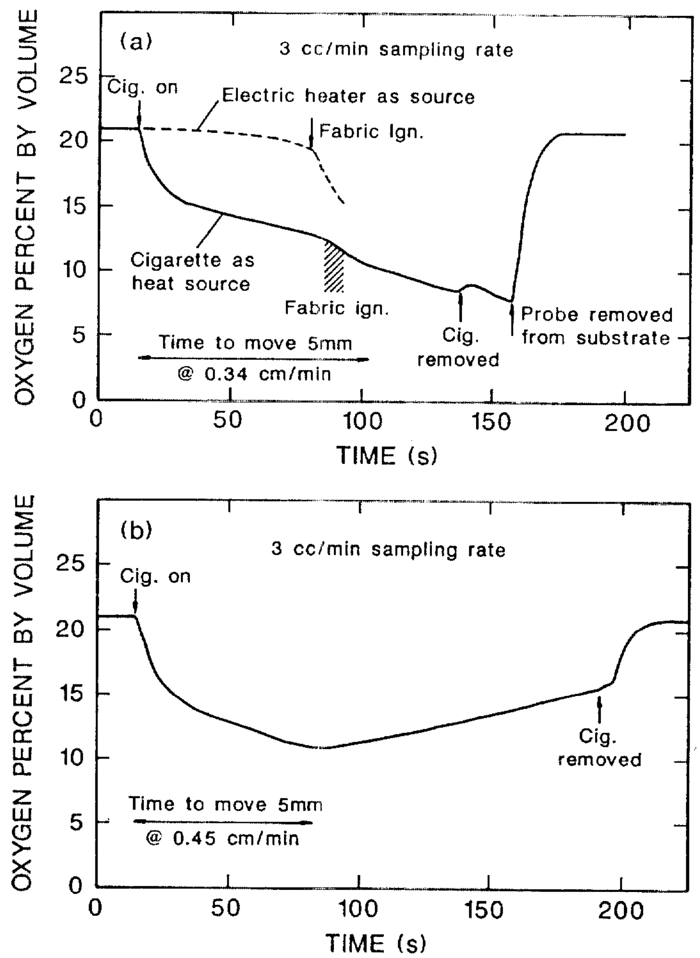
Another possible source of deviation from the purely heat flux-dominated ignition process described above was alluded to previously: the cigarette coal depletes the oxygen in the substrate. The rate of heat generation in the substrate which leads to fabric ignition is expected to follow an overall rate law of the form

$$Q'Z(\rho_{OX})^a(\rho_{CHAR})^b\exp(-E/RT) \qquad (4\text{-}5)$$

Here Q′ is the heat released per unit mass of fabric char oxidized, Z is the effective frequency factor, $\rho_{OX}$ is the local mass concentration of oxygen, $\rho_{CHAR}$ is the local mass concentration of fabric char, E is the effective activation energy of the oxidation process, R is the gas constant and T is the local temperature. Such a rate expression is usual for ignition problems [4-16]. The power dependence on $\rho_{OX}$ is usually less than or equal to first order; the temperature dependence is thus much stronger than the oxygen dependence. Nonetheless, there is some significant oxygen dependence. As the rate of heat release in the fabric begins to rise rapidly in response to the Arrhenius temperature dependence, it is restrained by the local oxygen depletion due to the oxidation in the cigarette coal; the net effect should be to increase the necessary temperature that the char must achieve before its heat release rate reaches the critical level where it is self-sustaining and the char is actively smoldering. Because of the relative dependencies on temperature and oxygen in the above reaction expression, the restraint caused by oxygen depletion can be overcome by a relatively small fractional increase in temperature. For example, assume that the value of E lies in the range from 20 to 40 kcal/mole and that the ignition temperature in the absence of oxygen depletion is 500°C; also assume that the reaction is first order in oxygen concentration (worst case). Then depletion of the oxygen level in the char by a factor of two requires a 21 to 43°C (factor of 1.03 to 1.06) increase in temperature to again achieve the same rate of heat release. These are small but not necessarily negligible increases in ignition temperature; if a cigarette is a marginal heat source for the ignition of a given substrate, this oxygen depletion effect could make the difference between ignition and non-ignition. More relevant in the present context, however, is the difference in oxygen depletion among cigarettes; one wishes to know whether such differences are responsible for some of the scatter in the preceding attempts to correlate ignition tendency with purely heat transfer-related properties of the cigarettes.

The technique used to assess the extent of oxygen depletion in the fabric during cigarette ignition was described previously; recall that the measurements were made between the fabric and the polyurethane foam in flat, horizontal substrates. Figure 4-26 shows typical results for the sampled oxygen percentage as a function of time from just before cigarette contact onward. Figure 4-26(a) shows the result for a fabric/cigarette combination which gave initiation of rapid fabric char oxidation (ignition as defined in this section); Figure 4-26(b) shows the result for a combination which did not. In both cases, the slow decay in oxygen level after the initial fast transient is caused by the coal moving over the sampling point. Note that in one case the oxygen level drops to 12½% at the time when the fabric ignites; in the other case the oxygen drops to 11% then begins to recover. The failure of ignition to occur in the second case is not due to the slightly greater oxygen depletion; the California fabric simply does not sustain smolder on the polyurethane foam even when it is first ignited while off of the foam, with a much more vigorous heat source, and then placed on it.

**Figure 4-26. Oxygen Depletion (as a function of time) Beneath Fabric**
**a) FNHC-25 on Splendor Fabric/2045 PU Foam; Igniting Case**
**b) FNHC-25 on Calif. Fabric/2045 PU Foam; Non-Igniting Case**



## Table 4-6. Summary of Oxygen Measurements During Ignition

| Cigarette | Substrate | Probe Gas Flow (cc/min) | Minimum $O_2$ Before Ignition (%) | Comment[a] Number |
|---|---|---|---|---|
| FNHC-25 | SPLENDOR/2045 FOAM | 30 | ≃14.5 | (1) |
| FNHC-25 | SPLENDOR/2045 FOAM | 30 | ≃14.5 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 30 | ≃15 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 13 | 16.5 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 14 | 16-17 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 7 | ≃12 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 7.7 | ≃12.5 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 3 | ≃11 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 3 | ≃12.5 | " |
| FNHC-25 | SPLENDOR/2045 FOAM | 3 | ≃12 | " |
| BELN-21 | SPLENDOR/2045 FOAM | 3 | 16.8 | (2) |
| BELN-21 | SPLENDOR/2045 FOAM | 3 | ≃17 | " |
| BELN-21 | SPLENDOR/2045 FOAM | 3 | ≃16-16.5 | " |
| BEHC-21 | SPLENDOR/2045 FOAM | 3 | 15.5 | — |
| BEHC-21 | SPLENDOR/2045 FOAM | 3 | 16.8 | — |
| FNHC-25 | SPLENDOR/2045 FOAM | 3[b] | 11.5 | — |
| FNHC-25 | CALIFORNIA/2045 FOAM | 3 | 12 | (2) |
| FNHC-25 | CALIFORNIA/2045 FOAM | 3 | 9.2 | " |
| FNHC-25 | CALIFORNIA/2045 FOAM | 3 | 10.8 | " |
| FNHC-25 | DENIM/2045 FOAM | 3 | 9.2 | (3) |
| FNHC-25 | DENIM/2045 FOAM | 3 | 8.2 | " |
| FNHC-25 | DENIM[c]/2045 FOAM | 3 | 11.8 | (4) |
| FNHC-25 | DENIM[c]/2045 FOAM | 3 | 12.9 | " |
| FNHC-25 | SPLENDOR[c]/2045 FOAM | 3 | ≃13 | — |
| FNHC-25 | SPLENDOR[c]/2045 FOAM | 3 | ≃14 | (4) |
| FNHC-25 | SPLENDOR[c]/2045 FOAM | 3 | ≃14.4 | " |

(a) Comments: (1) Fabric ign. caused further oxygen decrease subsequently
(2) No fabric ign.
(3) Minimum shown is due to cig. plus fabric smolder
(4) Minimum shown is due to cig. plus fabric smolder
(b) Fine needle probe
(c) Washed fabric

Table 4-6 summarizes the oxygen depletion measurements. There is some dependence of the minimum oxygen level on both cigarette and fabric. Note that the three cigarettes differ substantially in their ignition tendency. FNHC-25 (#127) gave 20 substrate ignitions, BEHC-21 (#107) gave 11 and BELN-21 (#106) gave one. Close examination of Table 4-6, comparing these cigarettes for minima due to the cigarette smolder only, shows that the range of oxygen minima is from about 11 to 17%. By the same type of calculation procedure done above, one can show that this difference in oxygen levels can cause a difference in ignition temperature of 13 to 27°C for values of E in the range noted above and with a first order oxygen dependence. Thermal analysis (TGA) results (air, 0.5 to 5°C/min.) for the fabrics in Table 4-6 give E values in the range from 33 to 36 kcal/mole. The order of the reaction with respect to oxygen has not been obtained for these fabrics but for another cellulosic material, tobacco char, Muramatsu found the order to be one-half [4-17]. With both of these likely parameter values taken into account, the observed range of oxygen depletion levels is likely to produce only a 6 to 8°C variation in ignition temperature. Thus it appears that oxygen depletion effects in the substrate are a secondary source of scatter in the preceding heat transfer correlations, at most.

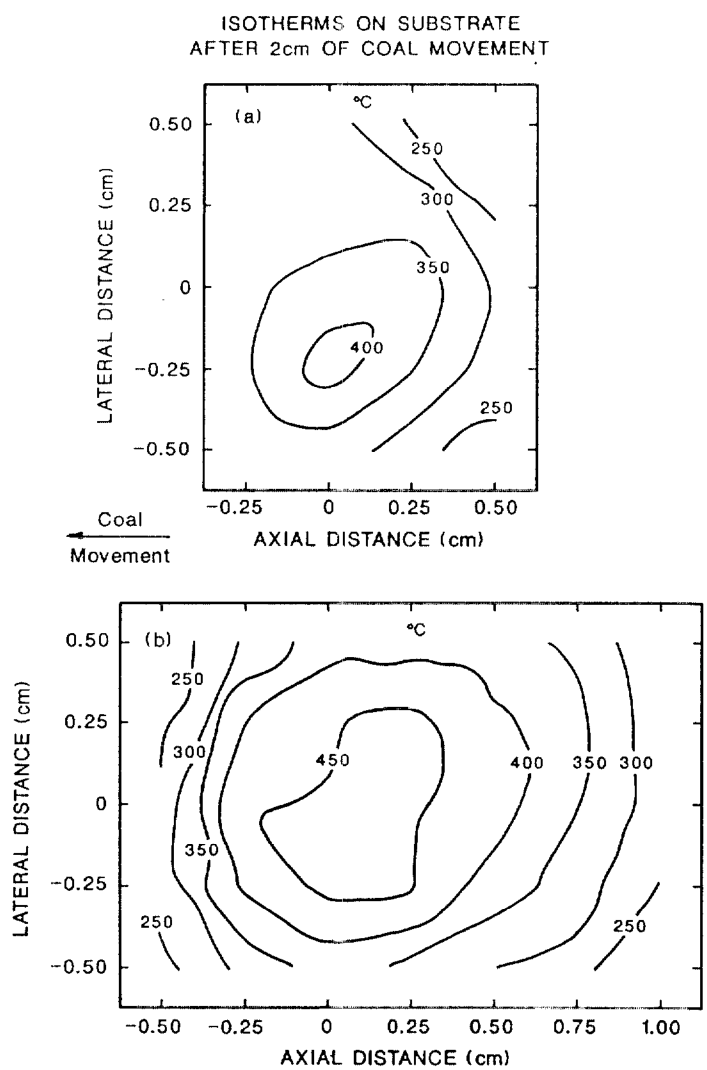
Figure 4-26(a) also shows the oxygen depletion for a typical case in which the cigarette has been replaced by a non-oxidative heat source, an electric heater. The source is the end of a 9.5 mm diameter rod heater which is hot enough to glow dull orange; the heater stays about 2 mm above the fabric surface and provides a peak incident flux on that surface of about 2½ to 3 W/cm². The half-height peak width is about 1 cm. This relatively large heated area (plus the lack of oxygen depletion) made it possible for this relatively low peak flux to yield the same ignition time as a cigarette providing a higher peak flux. The drastic decrease in oxygen depletion when a cigarette is not the heat source indicates that there is minimal, if any, oxygen consumption in the process of degrading the fabric and foam in the substrate. Recall that the issue of the thermicity of the substrate prior to ignition was addressed previously. The present result is not proof that no exothermicity exists but it does indicate that it must be much less than the rate of heat release from the cigarette. The depletion that does exist with the electric heater may be due only to local oxygen dilution by the degradation products evolving from the fabric and foam.

## Substrate Temperatures

The differing incident heat flux profiles discussed above should be reflected in differing temperature distributions in any substrate with which these cigarettes come into contact. This was explored first with an inert substrate to avoid possible complications due to any reaction heats. The substrate was chosen for its homogeneity and low thermal responsivity (to avoid distortion of the cigarette coal): the material was a calcium silicate insulation board with a density of 0.22 g/cm³. It was kept in a desiccator prior to testing; thermal analysis showed a small weight loss (≃ 10%) over the temperature range from 25 to 500°C, but no quantifiable heat effect accompanied this loss. The initial measurements were with two thermocouples imbedded in the top surface of the board; these were 0.05 cm diameter chromel/alumel thermocouples spaced 1.0 cm apart along the direction of the cigarette axis. Cigarettes previously ignited and allowed to smolder for a period of two minutes were placed on the board in such a position that the coal would move over the two thermocouples within the succeeding few minutes. The time for the paper burn line to reach the first thermocouple was varied from ⅔ to 3 minutes. The results of these measurements are summarized in Table 4-7. The peak temperatures (except for thermocouple #2 with FNHC-25 (#127)) follow the expected order implied by the number of substrate ignitions. Note that the peak temperature is not simply dictated by the peak flux; FNHC-25 (#127) and BELN-21 (#106) have virtually the same peak flux in this configuration (see Figure 4-19). Recall that the former cigarette has a coal length that is about twice as long as the latter and this affects the peak temperature because of the three-dimensional nature of the heat flow in the substrate. Note that the difference in temperatures between the two thermocouples does not appear to give a

**Figure 4-27. Isotherm Contours on the Top Surface of a Horizontal Flat Upholstery Mock-up (California fabric/2045 foam)**

**a) Cigarette BELN-21 (#106); time = 226 seconds**
**b) Cigarette FNHC-25 (#127); time = 368 seconds**



## Table 4-7. Temperatures[a] on Surface of Calcium Silicate Board Induced by Cigarettes

| Cigarette | No. of Substrate Ignitions | Temperature at TC#1 When Burn Line Passes TC#1 (deg. C) | Peak Temperature atTC#1 (deg. C) | Peak Temperature at TC#2 (deg. C) | (TC#1 – TC#2) When Burn Line Reaches TC#1 (deg. C) |
|---|---|---|---|---|---|
| FNHC-25 | 20 | 417 ± 12 | 470 ± 10 | 434 ± 10[b] | 366 |
| BNLN-21 | 12 | 418 ± 12 | 460 ± 8 | 457 ± 9 | 378 |
| FEHN-21 | 12 | 380 ± 12 | 420 ± 14 | 432 ± 16 | 343 |
| BELN-21 | 1 | 355 ± 18 | 372 ± 30 | 389 ± 28 | 314 |

(a) Temperatures from thermocouples embedded in surface of calcium silicate board 1.0 cm apart along axis of cigarette coal movement. TC#1 is the first thermocouple over which the coal passes; TC#2 is the second
(b) Average of two points

good measure of the width of the flux distribution in the solid, possibly because the times preceding these measurements were not held fixed. There does not appear to be a significant upward trend of peak temperature with time, as seen by comparing the peak values at the two thermocouples; this may be because of the relatively long time at which these measurements were taken.

Figure 4-27 shows the isotherms on the top surface of an upholstery mock-up (California fabric/2045 polyurethane foam) caused by two of the experimental cigarettes. The two cigarettes differ substantially in their ignition tendency; BELN-21 (#106) yielded one substrate ignition out of a possible twenty in Section 3 (primary evaluation) and FNHC-25 (#127) yielded twenty ignitions. At the times shown in the figure, each cigarette had sat on the substrate just long enough for the paper burn line to have moved 2 cm. since the cigarette first came into contact with the substrate. These times are both sufficient for the temperature patterns to be in a nearly steady state. Recalling the difficulties in obtaining these types of patterns, one should not regard them as highly quantitative in an absolute sense; the temperatures are reasonable, but it is the relative patterns that are of greater interest. The patterns are somewhat irregular due both to video noise and to random fluctuations in the spatial distribution of the flux incident from the cigarettes. The 400°C isotherm is instructive since the fabric ignition temperatures reported previously were above this level. The area on the substrate surface which is enclosed by the 400°C isotherm is about 40 times larger in the case of FNHC-25 (#127) than for BELN-21 (#106). There is also a substantial area above 450°C with cigarette FNHC-25 (peak temperature 464°C) whereas the highest temperature with BELN-21 is 25°C below this level (peak temperature 424°C). Thus, no matter whether smolder initiation in the fabric requires achievement of a minimum ignition temperature at a point on the fabric or within some minimum volume of the fabric, it is clear that FNHC-25 will achieve such conditions more readily than will BELN-21. This is the result that one would expect on the basis of the preceding measurements of the incident flux characteristics of these cigarettes.

It is pertinent to note that the small difference in peak substrate temperatures (40°C) resulting from contact with cigarettes which differ greatly in ignition propensity implies that the fabric ignition process is only marginally achieved by the most ignition prone of the experimental cigarettes.

Measurements like those in Figure 27 would have been useful at several times for any given cigarette type and for more cigarette types as well; this would have provided further proof of the correspondence between the measured incident flux characteristics and the temperature buildup in the substrate that leads to smolder initiation. Unfortunately, time constraints prevented this.

# Summary and Conclusions

The studies reported in this section have helped clarify the relation between the cigarette and the smoldering ignition process it induces in upholstery substrates. It is apparent that this relation is quite complex even before any rapid exothermic reactions begin in the fabric. The cigarette coal is altered by the proximity of a substrate and it is altered by efforts to measure the heat flux incident from the coal to a substrate.

The heat flux that has been measured for a large number of the experimental cigarettes is the "cold wall" value which pertains to the very early stages of heat-up of a substrate. The major emphasis has been on obtaining the flux distribution along the longitudinal axis of the cigarettes. The errors in measuring these flux profiles are such as to make the peak flux values obtained as much as 25-30% lower than the actual values. The axial heat flux profiles are thus most useful for comparative purposes. They are found to vary both with the geometric configuration of the adjacent substrate (if any) and with the design parameters of the cigarette. The variation with configuration can be largely explained on the basis of adjustments the cigarette coal makes to its rate of oxygen supply; heat losses appear to interact with these adjustments. The design parameters of the experimental cigarettes have little impact on their peak coal surface temperatures and hence their peak heat flux; this latter parameter could not be shown to have a statistically significant correlation with the ignition propensity of the cigarettes examined here even though there is good reason to believe that it must if it could be varied significantly (Section 5).

Cigarette design does substantially affect the smolder velocity and the coal length. These two parameters combine to influence the total heat input from a moving cigarette coal to a fixed point on a substrate surface. Total heat input is found, however, to correlate only approximately with substrate ignition tendency. The best correlation (though by no means perfect) is found between a measure of coal area and ignition tendency; a related correlation exists between mass burning rate and ignition tendency. The partial correlation with coal area implies that the three-dimensional nature of the heat flow in a substrate in response to local heating by a cigarette coal is a major factor in determining whether the fabric beneath the cigarette coal will become hot enough to begin to smolder.

There is significant oxygen depletion in the fabric during its heating by a cigarette coal; this could be sufficient to raise the effective ignition temperature a few tens of degrees. However, the variation in this depletion among cigarettes of differing design does not appear to be significant as a factor helping to explain their differing ignition propensities. The limited data on the cigarette-induced temperature distributions on the top surface of both inert and reactive substrates are generally consistent with the conclusions inferred above.

The results here provide both important clues as to how to lower the ignition propensity of cigarettes and an extensive experimental base on which to build and test models of the ignition process. For the latter they are particularly important for clarifying and quantifying the nature and extent of the cigarette/substrate interaction during ignition, providing flux distributions pertinent to various configurations. The next section provides further probing of these issues.

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The Effect of
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on the Ignition
of Soft Furnishings

## Section 5

# Modeling Ignition

## Contents for Section 5



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# Introduction

In Section 3, the results of ignition tests made with a few selected cigarettes were described. These yielded fluctuating but statistically significant results for a few choices of each of five cigarette parameters: tobacco type, cigarette density, paper permeability, chemical treatment of the paper, and cigarette circumference. In this section, we will consider the mathematical modeling of cigarettes, substrate, and of their interactions. Among other advantages, a valid mathematical model has the great virtue that not only will it correctly predict the results for such discrete parametric choices, but that it can correctly predict the results for intermediate choices of parameters – i.e. it permits smooth interpolation of results. Moreover, assuming it does everything right, it can *extrapolate* – i.e., predict the results for cases outside the parametric bounds of the experiments. Indeed, it should make correct predictions for the results from entirely novel combinations.

The purpose of this study is to predict theoretically whether or not an upholstered furniture item will be ignited to smoldering when a lit cigarette is dropped on it. To do this, the heating of the substrate when subjected to a moving heat source must first be accurately modeled, and a criterion established for its ignition. In order to examine how changing one or more properties of the cigarette will influence its ignition propensity, it is also necessary to understand the behavior of a smoldering cigarette. This includes knowing how its external heat flux and burning velocity depend on its various geometrical, physical, and/or chemical properties, and how these processes are modified when the cigarette lies on the substrate.

To make such predictions, the physics and chemistry of pyrolysis and of simultaneous heat and gas transport in a cigarette must be expressed by a set of mathematical equations. Since it is extremely unlikely that analytic solutions of these equations will be possible, procedures must be devised for solving these model equations numerically, on a computer.

Finally, we need to understand and describe how the cigarette and substrate influence each other, when in contact. In this section, three models are developed: (1) the computer model TEMPSUB, which yields the time-dependent temperature distribution in a substrate when it is exposed to a moving heat flux; (2) the computer model CIG25, which gives the time-dependent distributions of temperature, oxygen concentration, gas velocity, and burning rate in a freely-smoldering cigarette with user-prescribed properties; and (3) a model for the interaction of the cigarette and substrate when they are in contact; this gives the heat flux from a cigarette to the substrate.

The next sections present the details pertaining to substrate heating, modeling a freely-smoldering cigarette, modeling the interactions, and the procedure to be used for getting the flux to use in the substrate program. The results obtained with, and a partial validation of, the models are given last.

In order to place the cigarette-modeling effort into perspective, the next subsection gives a brief account of the physics of cigarette smoldering and a description of earlier cigarette models.

# Background

Understanding the smoldering cigarette has received a good deal of effort, both experimental and theoretical. In this section, a brief, qualitative discussion of the dynamical processes which occur will be presented, the salient results from earlier experiments noted, and some of the principal efforts made to model a cigarette, discussed. It is not intended to be an exhaustive review.

## Cigarette Dynamics

A cigarette consists of small strands of cured tobacco leaf, held in a cylindrical shape by a paper wrapping. The cylinder has a circumference of 20 to 25 mm; it is usually circular in cross-section, with radius R. The paper is chemically treated to burn at about the same rate as the tobacco, and has permeability within specific limits. Often there is a filter at one end. A schematic illustration of a smoldering cigarette in its quiescent phase is given in Figure 5-1. The section marked C in this figure is char, most of which is oxidizing at a rate sufficient to make it glow. The peak temperature in this region is about 800 to 850°C, i.e. 1100 ± 25 K. The glowing coal is shaped more or less like a thick cone. The cone length varies, but is usually (see Section 4) on the order of 1 cm in length. Some of the heat from this reaction is carried back towards the virgin tobacco (the zone marked VT in the figure); this occurs partly by thermal diffusion, partly by radiation, and partly by convection of hot gases. This heat dehydrates and decomposes the tobacco behind the char – this is the (shaded) region marked P in the figure (P for "pyrolyzing"). This is the region from which a visible plume of smoke (marked S) rises. At the very front of the cigarette is the residual and evanescent ash, marked A and EA, respectively, in the figure.

For all commercial cigarettes, the paper decomposes and burns at the same velocity as the tobacco; this occurs in a thin region, on the order of 1 mm in width. Although the paper is permeable, most of the oxygen which is needed to sustain combustion diffuses into the cigarette in front of the paper burn line. That it must diffuse inward is clear, since the volume of air needed to consume the cigarette is about 1000 times the volume of the solid. This study only considers the quiescent phase of smoldering – i.e., between puffs – since that is the situation when it lies on the substrate.

The measured temperature distribution in the smoldering cigarette is shown by the isotherms in Figure 5-2, taken from Baker [5-1]. Figure 5-3, taken from the same reference, shows the (measured) volume percentage of oxygen. Note that this value is essentially zero in the region of maximum temperature, so that the reaction (oxidation) rate there is low, in spite of the high temperature.

It can be seen that the smoldering is (as might be expected) cylindrically symmetric. Also – consistent with an oxygen-diffusion-controlled process – the oxygen concentration in the center drops to very low values. Generally, the *peak* reaction rates occur in the region where the mole fraction of oxygen, $x(O_2)$, is less than one percent. If the reaction rate is described by an Arrhenius expression, then it must be highly peaked in the high-temperature region. Indeed, the simple approximation of an infinitely high reaction rate occurring over a surface which is a paraboloid (or conoid) of revolution might be expected to have some

**Figure 5-1. Schematic of a Smoldering Cigarette. The region marked EA is "evanescent" ash, which normally falls off. It remains in place only when resting on the substrate. For the meaning of the other symbols, see the text. Note that the orientation is the reverse of that shown in Figures 5-2 and 5-3.**

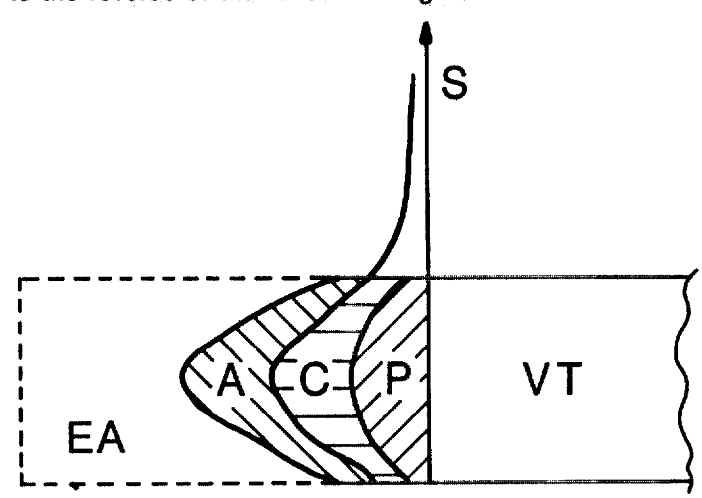
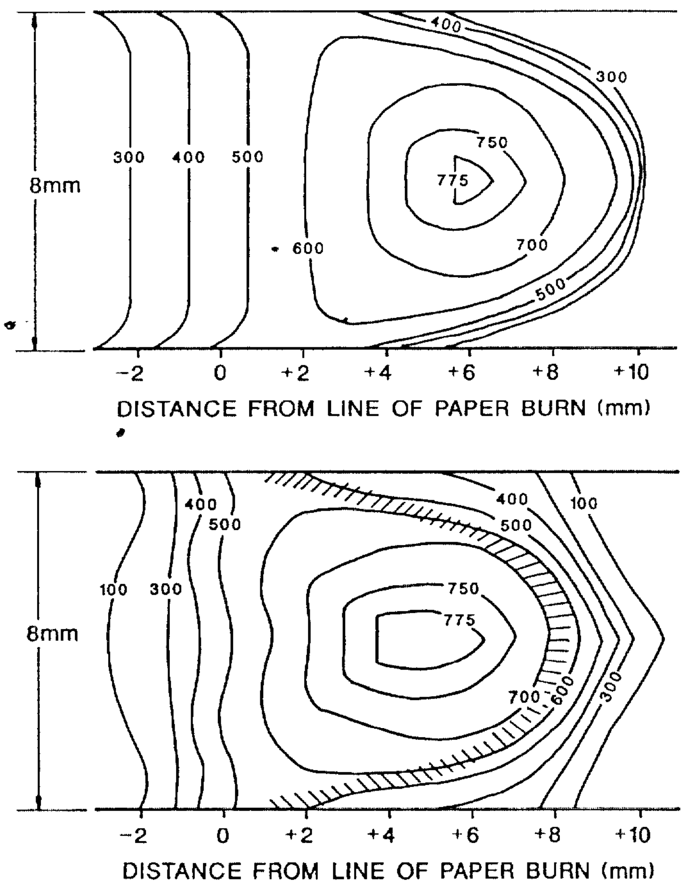


**Figure 5-2. Temperature Distributions (in °C) at and near the Hot Coal, Shortly After a Draw.** **The Upper Figure Shows the Temperatures in the Solid; the Lower Figure, that in the Gases. The Shaded Region in Explained in the Text. From Baker [5-1].**




validity (see Ref. [5-15]). In reality, this "surface" is a thin *region*. Since the oxygen concentration increases as the outer surface is approached, we would expect that this region is thickest at the periphery, where the peak surface temperature is 550-600°C, and grows thinner towards the center, with a slightly higher temperature; this region is shown in the lower of the two figures in Figure 5-2 by the shaded paraboloid. The highest temperatures occur behind the highly active shell. Thus, suppose an observer were positioned at x = 0 — i.e., at the paper burn line. As time progresses and the smolder wave moves to the left (to the right, in Figure 5-1), the peak reactions occur in a contracting ring, starting at the periphery and contracting to a point, leaving ash on the outside of the ring.

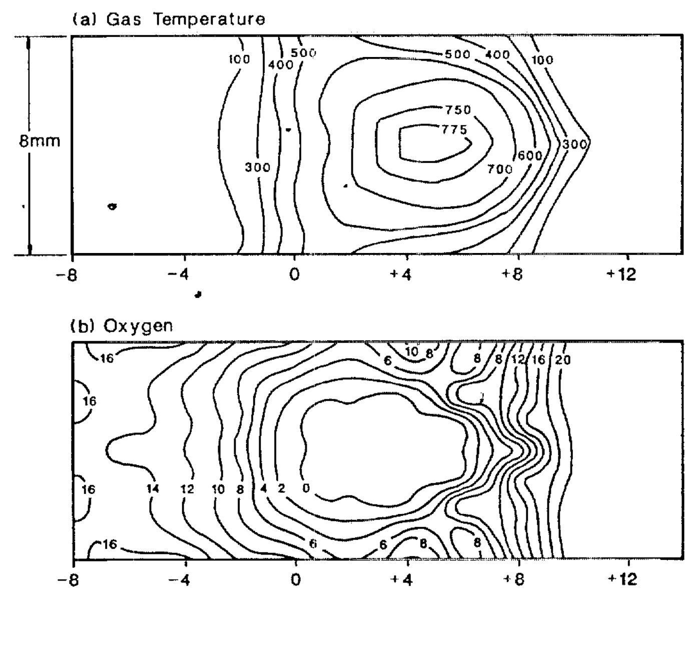
The distribution of surface temperature is a central question for our study, since the heat flux delivered to the substrate depends on it. Perhaps most important is the peak surface temperature there, $T_p$. Unfortunately, it is not an easy quantity to measure. Indeed, it is not even a well-defined quantity, since (as we see from Figure 5-2) the gas and the solid temperatures are not quite the same. Moreover, the result depends on the measurement technique. Baker's measurements yielded a peak surface temperature of about 550°C. Measurements reported in Section 4 yield peak temperatures in the range 650-700°C; however, these measurements are made with a thermocouple *inside* the paper wrapping, so that the surface temperature must be lower. Egerton *et al.* [5-7] found 616°C for $T_p$. Lendvay and Laszlo [5-8], using an IR technique, found that $T_p$ for their cigarettes was approximately 600°C. Since peak surface temperatures may well vary by 50°C among cigarettes, it is clear that $T_p = 600 \pm 50$°C.

Cigarettes vary within a factor of about 3 in the speed of propagation of the smolder wave: the average commercial cigarette is 6 to 7 cm long, and it takes between 10 and 30 minutes to be consumed, without drawing or puffing on it. The variations depend on the radius, on the packing density, on whether the tobacco leaf has been expanded or not, on the kind of tobacco, on the moisture content of the tobacco, on the cut width, and on the kind of paper, its permeability, and how it has been chemically treated. Note that, contrary to what is predicted by Muramatsu's model (see below) Samfield states that the moisture content does *not* affect its peak temperatures (Ref. [5-14]); rather, it affects the burning velocity, because it takes time (and energy) to evaporate the water.

## Previous Modeling Efforts

A number of attempts have been made to model smoldering cigarettes or analogous systems. All of them make some simplifying assumptions in order to make the problem tractable.

**Figure 5-3. Gas Temperature (°C) and Oxygen Concentration in the Quietly Smoldering Cigarette.** **From Baker, ref. [5-1].**



One of the early ones is that of Moussa, Toong, and Garris [5-2]. They experimented with, and then modelled, the smoldering and extinction of a cellulose cylinder without any paper wrapping. They assumed the smoldering to be steady-state, and they treated the problem as one-dimensional (hence, no radial gradients). They found: (a) (Experimentally) that the smoldering velocity is closely related to the maximum temperature in the cylinder, (b) reasonable agreement between theory and experiment for the extinguishment limit, (c) that the rate-limiting step in the combustion and hence in the rate of propagation is the diffusion of oxygen to the char, which is in good accord with experiment. They also (d) calculated values for v, the propagation velocity of the smolder wave. However, the calculation depends on an uncertain parameter, and the quantitative accuracy of the model is questionable.

A much more detailed model of a cigarette was produced by Summerfield *et al.* [5-3]. It considers a two-step process: pyrolysis to a char, followed by its oxidation. It ignores water evaporation. The char-oxidation reaction is assumed to be a linear function of the oxygen concentration. The combustion model is time-dependent rather than steady-state, and considers the paper covering, though only indirectly, *via* a varying surface permeability to oxygen. It has a sophisticated treatment of heat transfer inside the cigarette: it includes heat transfer by radiation, as well as by solid phase conduction. It is also a one-dimensional model. The model consists of ten simultaneous, coupled partial differential equations (PDEs), and the starting condition assumes the presence of fixed amounts of ash, char, and tobacco. The calculation predicts the burning velocity fairly well, as a function of draw rate. However, the dependence on oxygen mole fraction in the atmosphere is not so well predicted, although this is not important for the current purpose. The calculated gas temperature profile is fairly good: the peak is about right; but the width of the distribution is too narrow (see Section 4). Perhaps the main limitation for this project is that it is a steady-draw model, so that diffusion and natural convection within the cigarette are ignored.

The most elaborate model is that due to Muramatsu *et al.* [5-4,5]; it was developed in two stages. In Ref. [5-4] they develop a model for the pyrolysis of the cigarette. Their model is best described by quoting from their abstract:

*"A one-dimensional mathematical model for heat and mass balance has been proposed to elucidate the changes occurring in the temperature and density of the evaporation-pyrolysis zone in a naturally smoldering cigarette. The model considers: (1) pyrolysis of tobacco obeying Arrhenius kinetics, (2) evaporation of water from tobacco following a mass-transfer- and rate-determined process, (3) weight loss of tobacco due to pyrolysis and evaporation, (4) internal heat transfer characterized by effective thermal conductivity, (5) heat loss attributable to free convection and radiation from the outer surface of the cigarette and endothermicity of the evaporation process, and (6) smoldering speed. These processes are expressed in a set of simultaneous ordinary differential equations that can be solved numerically by the Runge-Kutta-Gill method."*

Furthermore, they assume the process is steady state, and, at this stage, *impose* the propagation velocity, v. They also ignore the convection or diffusion of gases other than water vapor. They take the existence of the paper wrapping into account only through its effect on the loss of water vapor.

These approximations are evidently adequate, as it yields good agreement between theory and experiment (see Ref. [5-1]) for the temperature and density along the axis in the pyrolysis-evaporation region. Position along the axis is given by x, where $x=0$ is the boundary between the pyrolysis region and the char-oxidation region. Thus, the agreement for T(x) and $\rho(x)$ is good for $x<0$ – i.e., before the char-oxidation region (not considered in this part of their model). For $x>0$, the calculated temperature profiles deviate substantially from measured ones, as might be expected. The dependence of the profiles on the imposed velocity, on the other hand, is not so well reproduced – there is only semi-quantitative agreement. Since this pyrolysis-zone model is one-dimensional, it does not give an R-dependence of the results.

In Ref. [5-5], Muramatsu developed a char-oxidation model which describes the processes occurring in the region $x>0$; this complements the pyrolysis/evaporation model developed in [5-4]. The model is quite detailed; it takes two char-oxidation reactions into account and is two-dimensional (cylindrically symmetric). Like all the other models it is a homogeneous model, i.e., it does not take the point-to-point heterogeneity of the cigarette (i.e., the fact that there are solid particles and a gaseous medium) into account directly. Energy loss is through radiation and convection at the outside surface of the cigarette. It is assumed that there is no temperature difference between the solid and gaseous phases. This is not a bad approximation, and simplifies the problem considerably. Heat transport by thermal radiation inside the cigarette is taken into account in a somewhat different way than is done in Summerfield *et al.* The thermal conductivity at any point is assumed to be isotropic. Similarly, the temperature dependence of the gaseous diffusivity is taken into account explicitly.

Finally, the pyrolysis/evaporation model and the char-oxidation model are tied together through an energy-flow matching condition at the pyrolysis/char-oxidation boundary to obtain the appropriate smolder velocity. There are still a few weaknesses in this formulation:

1. Any pyrolytic reactions in this region ($x>0$) are ignored;
2. The burning is assumed to be steady state;
3. The paper burn line must be coincident with the (forcibly) plane end of the pyrolysis zone;
4. Prior to decomposition, the paper wrapping is assumed to be impervious to oxygen; this should result in the cigarette going out, according to experiment;
5. Perhaps in order to be consistent with the above assumption, radial convection of gases is ignored; and



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6. If the calculation has not converged after 1000 iterations, the unconverged result is accepted as correct, nevertheless.

The results of calculations made by Muramatsu for six representative cigarettes are:

1. The peak temperatures, when expressed in °C, are only 2.7% to 5.7% higher than experimental data.

2. The smolder velocities are 14% high, on the average, varying between 4% low and 26% high.

3. The calculated variations of smolder rate (v) and peak temperature ($T_m$) with R (the cigarette radius), the packing density $\rho_p$, and the moisture content in the tobacco shreds are indistinguishable from the experimentally observed variations.

   The dependence of v and $T_m$ on ambient oxygen partial pressure is not well predicted (this is not an important consideration in this study).

4. The calculated distribution of temperature and oxygen concentration (in the char oxidation region) is in agreement with measurement, except for a scale factor (the predicted distribution is narrower than observed).

Because of this last point, Muramatsu *et al.*'s model cannot be used directly to obtain the flux emitted to the substrate: the too-narrow temperature distribution would substantially underpredict the energy output of the cigarette to the substrate. However, the model is excellent for some purposes; in particular, to estimate cigarette smolder velocities. The velocity is used in conjunction with a correlation found in this section (also see Eq. (4-1)) to obtain the axial width of the distribution of heat flux from the cigarette.

# Modeling the Substrate

## Thermal Physics

Smoldering ignition of a flammable substrate (i.e., furniture) results from that material being subjected to a sufficiently high heat flux for a sufficient length of time.

The substrates of interest are fabric-covered padding. For the sake of simplicity, however, this analysis assumes the substrate to be homogeneous, uniform, and inert. Thus, the model begins with a representation of the diffusion of the energy (supplied by the ignition source) within the substrate; the latter is a specified, external, slowly-moving flux; the presence of a cigarette is taken into account via appropriate boundary conditions.

The general equation for heat diffusion through a solid medium is [5-6]

$$\rho C \frac{\partial T}{\partial t} = \mathrm{div}(k \text{ grad } T) + S \qquad (5\text{-}1)$$

This equation relates the time rate of change of temperature (the left-hand side) at a point, to the temperature gradients at that point. Here S is any internal heat source (or sink), and the thermal conductivity k is a function of temperature, and hence a function of position. If the substrate is inert and does not contain water, then $S=0$, and any heat sources or sinks will appear only on the boundaries. Using a Cartesian coordinate system, z is the coordinate normal to the surface, with the origin on the surface. That is, $z=0$ *is* the surface. Thus the boundary condition is that the net flux into the surface is, at any point,

$$\phi_{net}(x,y,t) = -k\left(\frac{\partial T(x,y,z,t)}{\partial z}\right)_{z=0} - \phi_{in}(x,y,t) - \phi_{out}, \quad z=0,\ t>0 \qquad (5\text{-}2)$$

where $\phi_{in}$ is the flux from the moving heat source (cigarette) into the substrate normalized to ambient (see Eq. (5-81)), and $\phi_{out}$ is the (net) flux from the horizontal substrate to the overlying medium (cigarette or air):

$$\phi_{out}(x,y,t) = h(T_s - T_a) + \varepsilon_s\sigma(T_s^4 - T_a^4) \qquad (5\text{-}3)$$

Here $T_s = T(x,y,0,t)$ is the surface temperature
$k$ = thermal conductivity of the substrate
$T_a$ = the ambient temperature
$h$ = the convective heat loss coefficient, for points away from the cigarette
$\varepsilon_s$ = emissivity of the substrate surface (assumed uniform)
and $\sigma$ = Stefan-Boltzmann constant

For surface points *under* the cigarette, the first term on the right hand side of Eq. (5-3) represents conduction rather than convection. From the measured initial conduction flux from cigarette to substrate, 3.7 W/cm², one can infer that along the line of contact between the cigarette and substrate, the effective value of h is 74 W/m²°C; over the entire heated region (about 1 cm² in extent) the average value is 40 W/m²°C.

Thus, as the surface of the solid is being heated by the flux, it is being cooled by heat transfer through the solid; some of that heat is transported to other parts of the surface where it is lost to the atmosphere *via* convection and radiation.

The source flux at the surface, $\phi_{in}(x,y,t)$, is prescribed. For a source at the surface whose shape f(x,y) is fixed, but which moves at constant velocity v along the x axis, it is expressed as

$$\phi_{in}(x,y,0,t) = f(x - vt, y).$$

If the source is stationary, then analytic solutions of the problem are possible, assuming a *linear* rate of heat loss at the $z=0$ boundary ($\varepsilon_s = 0$). However, there is no simple analytic solution for a moving source, nor for the cases where radiative ($T^4$) cooling is taken into account. Hence a numerical procedure is required in general. When the source moves, the problem must be treated in three (spatial) dimensions. When the heated spot moves in a straight line along the surface, the problem simplifies slightly, because of the bilateral symmetry.

For the numerical solution, the substrate is subdivided by a grid; the source is a flux distribution over the surface mesh, and the movement of a source simply becomes a time-varying source over each grid point. The computer program TEMPSUB has been written, which solves Eq. (5-1) numerically, with the boundary condition (5-2). See Appendix 5A for details.

This program has been checked for accuracy and correctness for some special cases for which we have analytic solutions. It has also been checked for global energy balance; that is, the temperature distribution in the solid must be such that

$$\int_0^t dt' \iint \phi_{in}(x,y,t')dxdy = \rho C_p \iiint (T - T_i)dxdydz + \int_0^t dt' \iint \phi_{out}(x,y,t')dxdy \quad (5\text{-}4)$$

where $T_i$ is the initial temperature of the solid (assumed to be constant). With a grid size of 1.5 mm or less, and a sufficiently short time interval (see Appendix 5A), the maximum errors found in the calculated temperatures are about 1%, compared to the exact analytic expressions.

The program assumes that the impinging heat flux is of the form

$$\phi_{in}(x,y,t) = \phi_m \exp\left[\left(\frac{x - x_o - vt}{\sigma_x}\right)^2 - \frac{y^2}{\sigma_y^2}\right] \quad (5\text{-}5)$$

The user must input the peak flux $\phi_m$ (in W/m²), the initial peak position $x_o$, the standard deviations $\sigma_x$ and $\sigma_y$, and the velocity v, all in meters (or m/sec). The program also requires a thermal conductivity k and a thermal diffusivity $\alpha$ for the substrate material. The volume is divided into parallelepipeds whose size is user-chosen. The smallest practicable size is 1.5 mm on a side, for a substrate of size 6×6×3 cm deep. The user must be certain to choose a time interval $\Delta t$ for the calculation such that

$$\Delta t \leq (\Delta x)^2/12\alpha \quad (5\text{-}6)$$

The results will be shown later, and more detailed descriptions given in Appendix 5A.

## Ignition

The simplest ignition criterion is that a point on the surface reaches an "ignition temperature" $T_{ig}$, characteristic of that material; this is adequate for our purposes. It is then necessary to know whether, when (smoldering) ignition of the substrate occurs, this is shortly followed by self-extinguishment, or whether it is self-sustaining. The experimental observation is that the smoldering is usually self-sustaining under the circumstances with which we are concerned (see section 4).

When there is ignition, the term S in Eq. (5-1) ceases to be zero, and the calculation ceases to be valid thereafter. However, since all that is wanted to be determined is whether the substrate ignites, this is of no consequence.

## Possible Improvements

Although the program TEMPSUB is adequate, it could usefully be generalized in several ways. First, it assumes that the thermal diffusivity,

$$\alpha = k/\rho C,$$

is constant, whereas for most materials, at least the specific heat and thermal conductivity vary with temperature. If the variation is not large, this can be taken into account reasonably well by using some appropriate average value for $\alpha$. For porous media such as fabrics and foamed plastics, there will be substantial heat transfer by (internal) radiation, so that there will be a significant nonlinear temperature dependence of k. Second, the fact that the thermal characteristics of the padding are different from those of the fabric should be taken into account. Third, since most fabrics are fibrous/porous, they should be treated as diathermanous slabs—i.e., heating and cooling by radiation should be treated in depth. Fourth, moisture evaporation and movement should be taken into account.

It may also be that melting and/or charring of the fabric and the padding should be considered; in fact, foam padding can (locally) shrink away from the fabric prior to the latter's ignition. Still another complication is that generally neither the fabric nor the padding is homogeneous. Finally, if either material is not inert, so that it pyrolyzes as its temperature rises, then the term S in Eq. (5-1) must be included; $S<0$ for endothermic pyrolysis, $S>0$ for exothermic pyrolysis. This would complicate the solution somewhat, assuming no material or oxygen depletion. If the pyrolytic process(es) do involve oxygen, then the problem becomes enormously more complicated, as the PDE's describing gas diffusion and convection must be solved together with the PDE (5-1).

# Modeling the Free Cigarette

The model of a cigarette must predict (a) the external heat flux from it, and the extent of the heating zone, (b) the velocity of smolder propagation, and (c) how these depend on: the radius of the cigarette (R), the tightness of packing (*via* the void fraction $\phi$), the type of tobacco (*via* its thermophysical and kinetic parameters: heat of gasification $H_v$, heat of combustion $H_c$, activation energies and pre-exponential factors, density $\rho$, thermal conductivity k, specific heat $C_p$, etc.), and the wrapping paper (its thickness, chemical composition, permeability, kinetic parameters, etc). Two alternative modeling approaches were pursued in parallel, intending that at least *one* would succeed in yielding the desired objective. The development of each benefitted from insights gained with the other. The first is a global, semi-quantitative model which borrows heavily from earlier modeling work. The second is a more detailed model based on first principles.

## Semi-Empirical Model

The first approach is to utilize existing experimentally or theoretically determined correlations in order to get the temperature and flux distributions, smolder velocities, etc.

### Burning Rate as a Function of Various Parameters

From Figures 9-4 to 9-7 of Section 9 of Muramatsu [5-5], we find the following experimental dependencies for smolder rate ( $\dot{m}$, in mg/min and v, in cm/min) and maximum interior temperature $T_m$ (in °C); bear in mind that these are for a cigarette in free burn, not on a substrate. As was shown in Section 4, however, the smoldering rate on a substrate is (to a first approximation) a constant fraction of the rate in free burn.

Dependence on cigarette radius:

$$\dot{m}(R) \simeq 17.2\ (2\pi R)\ \text{mg/min}, \qquad (5\text{-}7)$$

with R in cm; since

$$\dot{m} = \pi R^2 \rho v, \qquad (5\text{-}8)$$

then with $\rho$ = 0.259 g/cm³ (their reference value),[1]

$$v(R) \simeq \frac{2(17.2 \times 10^{-3})}{0.259\ R} \simeq \frac{0.133}{R}\ \text{cm/min} \qquad (5\text{-}9)$$

and $\quad T_m(R) \simeq \text{const.} \simeq 815°C \qquad (5\text{-}10)$

Dependence on packing density $\rho_P$:

with $\quad 2\pi R = 2.5$ cm,

$$\dot{m}(\rho_P) \simeq \text{const.} = 43\ \text{mg/min} \qquad (5\text{-}11)$$

and Eq. (5-7) yields

$$v(\rho_P) = 0.0865\ /\rho_P\ \text{cm/min} \qquad (5\text{-}12)$$

Also, $\quad T_m(\rho_T) = \text{const.} = 815°C$

Muramatsu also gives the dependence on moisture content and ambient oxygen partial pressure. The latter is of no interest to us, for our present purpose.

In Figures 9-8(a) - (e) of Ref. [5-5], a sensitivity analysis for some other parameters is given, but derived from the model rather than experimentally. These results show that the smolder velocity v and peak (interior) temperature $T_m$ are very weak functions of the pre-exponential factor for pyrolysis ($Z_p$), solid-phase thermal conductivity ($k_s$), and specific heat of tobacco ($C_v$). On the other hand, there is a perceptible dependence of v and $T_m$ on $Z_{co}$, the pre-exponential factor for the char-oxidation reaction:

$$v(Z_{co}) \simeq 0.168 + 0.178(Z/Z_o)\ \ \text{cm/min} \qquad (5\text{-}13)$$

where $Z_o$ is the reference value of $Z_{co}$, Z the actual value used. Similarly,

$$T_m(Z_{co}) \simeq 687 + 181\ Z/Z_o\ \ °C \qquad (5\text{-}14)$$

[1] *The coefficients in Eqs. (5-7) to (5-24) are given to three significant figures for calculation only; the final results are only valid to two significant figures. Note that cm/min must be converted to m/sec for use in the substrate program.*

The dependence on the mass transfer coefficient $K_g$ is very strong:

$$v(K_g) \simeq 0.240 + 1.94 \times 10^{-4} \exp(6K_g/K_{go}) \quad \text{cm/min} \tag{5-15}$$

and

$$T_m(K_g) \simeq 696 + 3.113 \exp(3.6 \, K_g/K_{go}) \quad {}^\circ\text{C} \tag{5-16}$$

where $K_{go} = 4.45$ cm/sec is the reference value. The dependence they found on the diffusion coefficient is even steeper; it is also rather more complicated, for v; a crude (but perhaps adequate) approximation to v(D) is

$$v(D) \simeq \begin{cases} 0.6 \, D/D_o - 0.276 & 0.86 \leq D/D_o \leq 1 \\ 1.38 \, D/D_o - 1.056 & 1 \leq D/D_o < 1.24 \end{cases} \tag{5-17}$$

where $D_o = 0.112$ cm²/sec is the reference value of D. For the peak temperature,

$$T_m(D) \simeq 262 + 548 \, D/D_o \quad {}^\circ\text{C} \tag{5-18}$$

The dependencies on thermal conductivity of the solid phase in the burning zone, $k_s$, are

$$v(k_s) \simeq 0.355 - 0.025 \, k_s/k_{so} \quad \text{cm/min} \tag{5-19}$$

and

$$T_m(k_s) \simeq 958 - 132 \, k_s/k_{so} \quad {}^\circ\text{C} \tag{5-20}$$

where $k_{so} = 3.16 \times 10^{-3}$ W/cm°C is the reference value.

The dependencies on the radiative emissivity from the outer surface burning zone, $\varepsilon_s$, are

$$v(\varepsilon_s) \simeq 0.711 - 0.38 \, \varepsilon_s/\varepsilon_{so} \quad \text{cm/min} \tag{5-21}$$

and

$$T_m(\varepsilon_s) \simeq 1085 - 270 \, \varepsilon_s/\varepsilon_{so} \quad {}^\circ\text{C} \tag{5-22}$$

where $\varepsilon \equiv \varepsilon_{so}$ is the reference value ($\varepsilon_{so} = 0.73$).

Finally, the dependencies on $Q_h \equiv H_c$, the heat evolved by smoldering, are

$$v(H_c) \simeq 1.6 \, H_c/H_{co} - 1.269 \quad \text{cm/min} \tag{5-23}$$

and

$$T_m(H_c) \simeq 1060 \, Hc/H_{co} - 237 \quad {}^\circ\text{C} \tag{5-24}$$

where $H_{co}$ is the reference value of the heat of combustion ($H_{co}$ = 4200 cal/gm = 17570 J/gm).

These expressions are only approximate, because they were obtained by the author from Muramatsu's figures by a curve-fitting exercise. One might possibly do better by referring to Muramatsu's original figures. A possible drawback to this formulation (not actually inherent in Muramatsu's model) is that the nonlinearities of the system are ignored. That is, it must be assumed that the factors are independent. This may still be adequate. That possible drawback can be entirely avoided by using the cigarette model CIG25 described earlier; that involves extensive computations, however.

We now have expressions for v and $T_m$ for almost any cigarette for which the thermophysical parameters can be specified. These do not yet (quite) satisfy what is required for the problem, as will be seen in the next subsection. However, a correlation is then found which enables one to find the heat flux to the substrate (to a first approximation), from a knowledge of v (or $\dot{m}$) alone.

### The Surface Heat Flux

In this section, the heat fluxes and the energy balance for the cigarette are discussed, and how they are related to its measured surface temperature distribution. The detailed calculations appear in Appendix 5C. In order to find the heat flux from a cigarette to the substrate, it is useful to see what the heat fluxes are in free burn, and then calculate how they are modified by contact with the substrate. The isolated cigarette is first considered here, and the cigarette on a substrate in the next section.

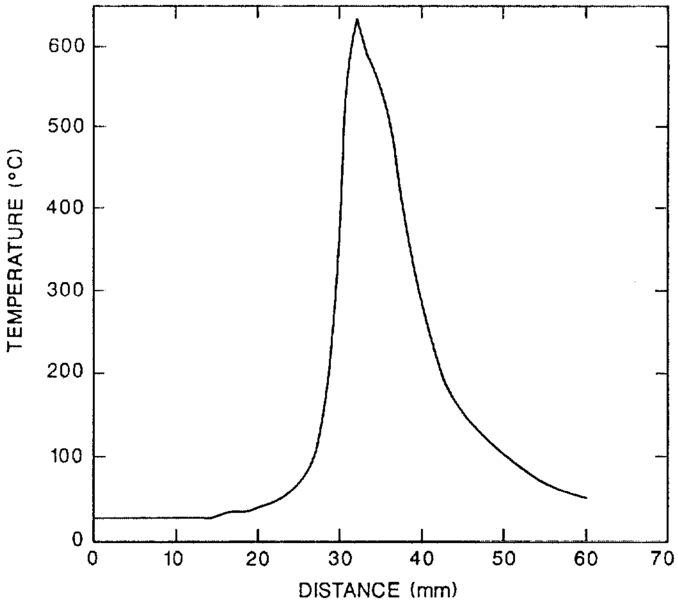
A cigarette contains m grams of tobacco, which release $mH_c$ joules of energy when it smolders. A fraction $\chi_s$ of this is required to heat up the solid and to pyrolyze it to char. A fraction $\chi_c$ is convected away, and a fraction $\chi_r$ is radiated away. When it lies on a substrate these fractions change, and there is an additional loss by conduction; that fraction is $\chi_{cd}$. $\chi_s$, $\chi_c$, $\chi_{cd}$, and $\chi_r$ may be functions of local conditions, such as the partial pressure of ambient oxygen, the rate at which the cigarette burns, and whether or not it is in contact with a substrate. They may each be a function of time, as well. From conservation of energy,

$$\chi_{cd}(t) + \chi_s(t) + \chi_c(t) + \chi_r(t) = 1 \tag{5-25}$$

Thus, in the time required to burn the entire cigarette, it releases $\chi_c mH_c$ joules *via* convection and $\chi_r mH_c$ *via* radiation (where $\chi_c$ and $\chi_r$ are the time-averaged values). The total energy output for a particular (experimental) cigarette will now be found from its measured smolder velocity. The separate convective and radiative loss rates will then be inferred from the surface temperature measurements, and the energy production and loss compared.

At any moment, the surface temperature of the smoldering cigarette is, (as can be seen from Figure (5-2)), a function with a single peak. This is displayed in Figure (5-4) for one of the experimental cigarettes used in this study (#105). However, these measurements were made inside the cigarette wrapping (as close to the periphery as was instrumentally practicable). The actual peak *surface* temperature was lower than this, as discussed in the next section. This curve must therefore be appropriately modified before it is used for any calculations. The modification is discussed in detail in Appendix 5C.

**Figure 5-4. Measured Longitudinal Surface Temperature Distribution for Cigarette 105**




The total energy output rate of the cigarette is

$$\dot{E}_t = \dot{m}H_c \tag{5-27}$$

Measurements made by Muramatsu *et al.* [5-4] (Table 5-5) showed that when the enthalpy lost from a representative sample of cigarettes by outgassing is excluded, the average net heat of combustion is

$$H_c = 1440 \text{ cal/g} \simeq 6010 \text{ J/gm. (of tobacco)}$$

With the packing density and burning velocity measured for this cigarette, the energy production rate

$$\dot{E}_{tot} \simeq 4.52 \text{ watts}$$

can be inferred.

The net radiative flux from this surface is

$$\phi_r(x,t) = \varepsilon_c\sigma[T^4(x,t) - T_a^4] \tag{5-28}$$

while the net convective flux is

$$\phi_c(x,t) = h[T(x,t) - T_a] \tag{5-29}$$

In these expressions, T is in Kelvins, $T_a$ is the ambient temperature (in K) and $\varepsilon_c$ is the emissivity of the cigarette surface.

In Appendix 5C, it is shown that from the longitudinal temperature distribution T(x) measured near the surface of cigarette 105 (shown in Figure (5-4)) and Eqs. (5-28) and (5-29), one can infer that when it burns in the open air, the convective and radiative losses are about

$$\dot{E}_c \simeq 2.02 \text{ watts}$$

and

$$\dot{E}_r \simeq 2.49 \text{ watts,}$$

respectively.

There is a small difference $\dot{E}_t - \dot{E}_r - \dot{E}_c$ between the production and loss rates, due to the energy deposited in the cigarette, averaged over the smolder period. Thus, the energy leaves by convection and radiation in comparable amounts, in free burn. The analogous results for the case where the cigarette lies on the substrate will be analyzed in the section on interactions.

It would be useful to measure the emitted flux directly, so as to check these theoretical estimates. When a flux gauge is run along the cigarette, however, what is measured is the radiative plus the *conductive* flux to the gauge. Therefore, a direct comparison is not possible, and a detailed analysis is required. The results of these flux gauge measurements and their analysis are given in the next section. It will also be shown there how the heat fluxes in the open relate to the heat flux to the substrate. Before doing that, however, a very useful result can be obtained as shown in the following section.

### Correlation Between v and $\ell_c$

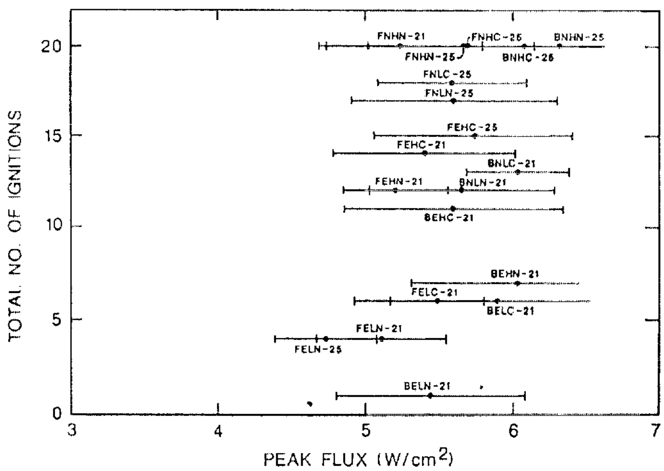
The heating flux from the cigarette will be expressed in the (approximate) form, Eq. (5-5). Therefore we need to know the four parameters $\phi_m$, v, $\sigma_x$, and $\sigma_y$. The flux used as a heat source for the calculation of the substrate temperature has been taken to have a peak value, $\phi_m$, which should be taken to be a function of time; however, the cigarette surface temperature will quickly stabilize, so that except for a brief and unimportant initial transient, it is indeed appropriate to choose $\phi_m$ as a constant. As pointed out in Section 4, the (similar) cooling of the cigarette by the cold gauge in its brief passage past the cigarette reduces the peak flux by 20-25%. We assume that this is about the same as the reduction due to the substrate; this assumption is borne out by the approximate consistency of the calculations made in subsection Interactions Between Cigarette and Substrate and Appendix 5C. The peak fluxes, $\phi_p$, measured while the cigarettes smoldered on a substrate, are plotted in Figure 5-5. It appears from this figure that $\phi_p$ is insensitive to the cigarette burned (from among the experimental cigarettes); a simple unweighted average of these data yield

$$\phi_p = 5.60 \pm 0.38 \text{ W/cm}^2$$

(0.38 W/cm² is one standard deviation; however, the error flags are large, and ± 0.8 W/cm² is a better reflection of reality). We shall return to this later. If $\phi_p$ is constant, it might be expected that the longitudinal (axial) width of the flux distribution (roughly, the length $\ell_c$ of the coal) should correlate closely with $\dot{m}$ (this is similar to the connection made in Eq. (4-1)). This correlation is readily demonstrated. First, note that

$$\dot{m} = \rho_p A v \tag{5-30}$$

**Figure 5-5. Peak Fluxes Measured by a Thermocouple, for a Representative Sample of Experimental Cigarettes Smoldering on a California Fabric/Foam Substrate**




where A is the cross sectional area of the cigarette. Usually, $A = \pi R^2$.

Also, $\dot{Q} = \dot{m} H_c$ is the power produced. The power *lost* while smoldering freely is

$$\dot{Q}_L = 2\pi R \int \phi(x)dx$$

*In the steady state,* they are equal, and therefore

$$\rho_p \pi R^2 v\ H_c = 2\pi R \int \phi(x)dx, \quad (5\text{-}31)$$

where v is the free-smolder velocity. Assume that the energy loss per unit length along CL (the line of contact with the substrate),

$$\dot{E}_P' = \int \phi(x)dx, \quad (5\text{-}32)$$

is proportional to the length of the coal and to the peak value of the heat flux measured by the gauge (in free space). That is,

$$\int \phi(x)dx \simeq \xi\ \ell_c \phi_p \quad (5\text{-}33)$$

where $\xi$ is the proportionality constant. (It is not obvious that Eq. (5-33) should hold, since $\phi_p$ measures the peak flux of radiation plus conduction to a cold surface, whereas $\phi(x)$ is the flux distribution of radiation plus convection while smoldering freely). Substituting Eq. (5-33) into (5-31), one obtains

$$\rho_P C v = \frac{4\pi}{H_c}\ \xi\ \phi_P\ \ell_c, \quad (5\text{-}34)$$

where C is the circumference. When $A = \pi R^2$, $C = 2\pi R$. The left hand side of Eq. (5-34) (where $\rho_P$, C, and v were found from measurements on the cigarettes) were plotted *vs* the (measured) coal lengths $\ell_c$. If $\phi_p$ were indeed constant, we should find that the values lie on a straight line going through the origin. The plot is shown in Figure 5-6, and it is clear that a good correlation indeed exists. If we ignore sample 27, which is an outlier, then the data can be fitted reasonably well with a straight line which goes through the origin; this is the line marked OL, and it corresponds to

$$\rho C v = 5.12 \times 10^{-3}\ \ell_c. \quad (5\text{-}35)$$

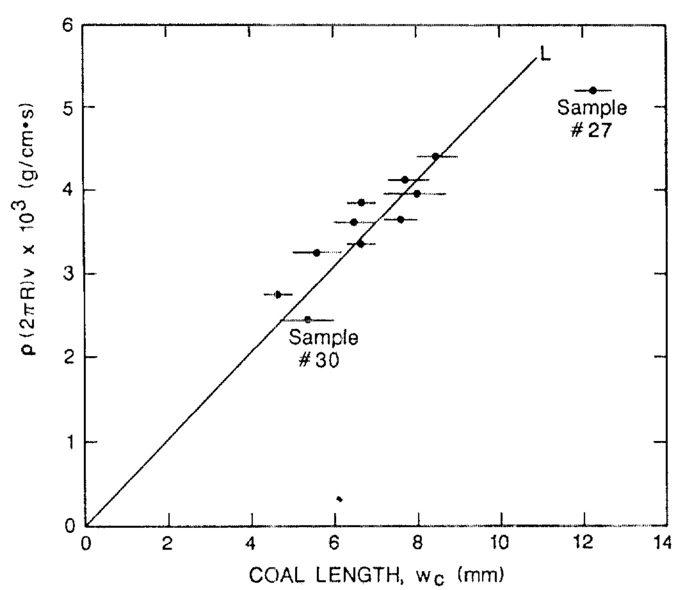
With $H_c$ = 6010 J/gm and $\phi_P$ =

5.60 W/cm², therefore, $\xi$ = 0.437.

If the *measured* peak fluxes were used, rather than the averages, the scatter is reduced, but only very slightly. Finally, investigation has shown that using the integrated values of the flux — i.e., $\int \phi_m(x)dx$ — rather than $\phi_p \ell_c$, does not improve the correlation (indeed, the scatter is worse).

Thus it has been shown that to a first approximation, the peak flux can indeed be taken to be constant. Moreover, Eqs. (5-6) to (5-24) can then be used to obtain v for any set of cigarette parameters, and Eq. (5-35) yields $\ell_c$. Later it will be shown how to relate $\sigma_x$ to $\ell_c$, and how to estimate $\sigma_y$. If one chooses $\phi_p$ for $\phi_m$, therefore, all four parameters needed to characterize the heating flux (*via* Eq. (5-5)) are available. This is the simplest quantitative model of cigarette-substrate interaction; an example of its use will be given later.

**Figure 5-6. Plot of ρCv *vs* $\ell_c$, the Coal Length, to Test Eq. (5-34).** **The Data are Given with Error Flags.**



## Detailed Model

The motivation for constructing a computer model of smoldering cigarettes has already been explained. In this section, the assumptions and equations required for a good cigarette model are outlined. The model which has actually been developed is only a subset of it. The complete model is outlined here nevertheless, in order to enable a user to add the missing pieces in the future, if desired.

We have seen that a good deal of detail is lost when the model is assumed to be one-dimensional. Therefore the time spent on making it two-dimensional (i.e., assuming cylindrical symmetry) was well spent. If a steady state were assumed, then the equations would simplify; however, it would then be necessary to choose the smolder velocity correctly (i.e., as an eigenvalue.) Moreover, if the equations are taken to be time-dependent, the heat and mass-transfer equations are parabolic partial differential equations (PDEs) which are easier to solve, in some ways: The convergence for the steady state equations is very slow (indeed, Muramatsu found that one thousand iterations would not suffice, at times), and it might actually be computationally faster to do the time-dependent problem. Also, this formulation yields v directly, whether or not it is constant. Finally, it is desirable to have a unified model, rather than separate pyrolysis and char-oxidation models, as Muramatsu has. For these reasons, it was decided to solve the time-dependent equations.

The following simplifying assumptions are made:

1. The cigarette is modeled with only *one* pyrolysis reaction and one char-oxidation reaction, rather than the six reactions chosen by Muramatsu.

2. Since the (internal) gas flow velocities depend on the pressure gradients, axial convection is neglected, as being much smaller than radial convection (since the axial gradients must be much smaller than the radial gradients).

3. The water (pre-existing or produced during combustion) in the tobacco column is also ignored. This may or may not be a good assumption, but it avoids yet another complication.

4. The tobacco column can be treated as a continuum – i.e., as a homogeneous, uniform mixture.

5. The tobacco shreds do not shrink as they lose mass.

6. The gas and solid phases are at the same temperature, locally, in the cigarette.

7. Species or temperature gradients within the tobacco shreds will be neglected, consistent with assumption No. 4.

8. Radiation transfer within the cigarette can be incorporated into an effective thermal conductivity.

9. The paper behavior appears only in the boundary conditions.

10. The gases generated or heated by combustion move radially outward to the side boundary (aside from diffusion). Thus there is a radial flow calculated strictly by mass conservation: The gas pressure within the cigarette is assumed to be only negligibly different from atmospheric, and therefore no momentum equations need be written.

11. The gas phase is quasi-steady. That is, $\partial \rho_g / \partial t = 0$.

12. Consistent with assumption #9, any (axial or radial) gradients in the paper are ignored; an effective mass transfer coefficient is used to model diffusion through the paper.

13. Assumption #8 is complemented with the assumption that the thermal conductivity is the same function of temperature throughout the cigarette – i.e., whether in ash, char or tobacco.

When the cigarette interacts with a substrate, two additional assumptions are made:

14. The cigarette combustion zone retains its cylindrical symmetry (observed to be approximately correct on fabric/foam substrates).

15. Prior to its ignition, the presence of the substrate has two effects on the cigarette, both of which can be assumed to apply symmetrically (on the average) to the entire cigarette periphery:

    (a) The oxygen supply to the cigarette is reduced by some factor

    (b) The thermal effects (e.g., as a heat sink) can be calculated in a decoupled manner (this assumption is weak, and may have to be dropped eventually).

The equations which describe the mass and energy transport in a smoldering cigarette will now be presented. Any additional simplifying assumptions will be indicated as each equation is discussed.

First, however, it is necessary to clarify some of the terms appearing in the equations. Consider the decomposition of the tobacco: one gram of tobacco, upon pyrolysis, produces $n_c$ grams of char. Assuming no reactions (with oxygen, nitrogen, etc.) the other $1\text{-}n_c$ grams will be gaseous products. Each gram of char reacts with $n_{O2}$ grams of oxygen to produce some heat, $n_A$ grams of ash, and $1 - n_A + n_{O2}$ grams of gaseous products of combustion. Since the combustion process mostly proceeds at very low oxygen concentrations, it can be expected to be inefficient – i.e., incomplete; and $n_{o2}$ is smaller than the stoichiometric value.

Mass Conservation:

$$\frac{\partial \rho_s}{\partial t} = -[(1 - n_C)R_p + (1 - n_A)R_{co}] \tag{5-36}$$

where $\rho_s$ is the mass density of the solid, $R_p$ is the pyrolysis rate (in gm/cm³ sec) and $R_{co}$ the char oxidation rate. The equation of continuity in cylindrical coordinates is

$$\frac{\partial}{\partial t}[\rho_s(1-\phi) + \rho_g\phi] + \frac{1}{r}\frac{\partial}{\partial r}(\phi\rho_g u_r r) = 0 \tag{5-37}$$

where r is the radial coordinate, $\rho_g$ is the mass density of gases, $\phi$ is the void fraction in the cigarette (i.e., the volume fraction of gas, rather than of tobacco shreds), and $u_r$ is the radial (convective) gas velocity. Axial convection has been dropped, by assumption #2. Since the shreds are assumed not to shrink, $\phi$ remains constant. Because of assumption #11, one can write

$$\frac{\partial}{\partial t}(\rho_g\phi) = \phi\frac{\partial \rho_g}{\partial t} \simeq 0, \tag{5-38}$$

and using Eq. (5-36), the equation for gas results:

$$\frac{\phi}{r}\frac{\partial}{\partial r}(\rho_g r\, u_r) = (1-\phi)[(1-n_C)R_p + (1-n_A)R_{co}] \tag{5-39}$$

One might define $\rho_A$, $\rho_C$, and $\rho_T$ as the ash, char, and tobacco densities and take them to be constant. Then if the total volume of solid is $V_s$ ($V_s = (1-\phi)V_{total}$), while those of ash, char, and tobacco are $V_A$, $V_C$, and $V_T$, respectively, it would follow that

$$\rho_s = \frac{1}{V_s}[\rho_T V_T + \rho_A V_A + \rho_C V_C]$$

However, it is more convenient to define the bulk densities

$$\rho_i \equiv m_i/V_s \qquad i = A, C, T \tag{5-40}$$

where $m_A$ = total mass of ash, etc. Then

$$\rho_S = \rho_A + \rho_C + \rho_T \tag{5-41}$$

and each of these bulk densities varies with time.

The equations for tobacco and char densities are very simple:

$$\frac{\partial \rho_T}{\partial t} = -R_p \tag{5-42}$$

and

$$\frac{\partial \rho_C}{\partial t} = n_C R_p - R_{co} \tag{5-43}$$

The equation for $\rho_A$,

$$\frac{\partial \rho_A}{\partial t} = n_A R_{co} \tag{5-44}$$

is not needed, since the ash is inert and simply accumulates. In the following equations, x is the axial coordinate. Rather than dealing with the oxygen density $\rho_{O2}$, the equations are written in terms of the oxygen mass fraction y:

$$y \equiv \rho_{O2}/\rho_g \tag{5-45}$$

Then mass conservation for oxygen is

$$\frac{\partial(\phi\rho_g y)}{\partial t} + \frac{\partial}{\partial x}(\dot{q}_x) - \frac{1}{r}\frac{\partial}{\partial r}(r\ \dot{q}_r) = -\frac{1}{r}\frac{\partial}{\partial r}(r\,\phi\, u_r\, y\, \rho_g) - n_{O2}(1-\phi)R_{co} \tag{5-46}$$

where $\dot{q}_x$ and $\dot{q}_r$ are the axial and radial oxygen mass fluxes from diffusion; that is,

$$\left.\begin{aligned} \dot{q}_x &= -\phi D_e \rho_g \frac{\partial y}{\partial x} \\ \dot{q}_r &= -\phi D_e \rho_g \frac{\partial y}{\partial r} \end{aligned}\right\} \tag{5-47}$$

where $D_e$ is the oxygen diffusion coefficient. Inserting Eqs. (5-47) into (5-46) and using the overall gas continuity equation, (5-46) becomes

$$\rho_g\frac{\partial y}{\partial t} + \rho_g u_r\frac{\partial y}{\partial r} = \frac{\partial}{\partial x}\left(\rho_g D_e\frac{\partial y}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\rho_g D_e\frac{\partial y}{\partial r}\right) - \left(\frac{1-\phi}{\phi}\right)\{y(1-n_C)R_p + [y(1-n_A) + n_{O2}]R_{co}\} \tag{5-48}$$

Next, consider the energy equation:

Assuming that the gas is quasi-stationary, as in Eq. (5-38), and that the specific heats of all gases are the same *and* independent of temperature, then the energy conservation equation can be written in terms of the temperature; it is

$$(1-\phi)\rho_s C_s\frac{\partial T}{\partial t} + \phi\rho_g u_r C_g\frac{\partial T}{\partial r} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) + (1-\phi)(Q_{co}R_{co} - Q_pR_p) \tag{5-49}$$

where $C_s$ = specific heat of the solid

$C_g$ = specific heat of the gases

k = thermal conductivity of the cigarette (see assumption #13)

$Q_{co}$ = energy released from char oxidation (lower heat of combustion)

and $Q_p$ = energy absorbed in (endothermic) pyrolysis

The internal heat transfer has a radiative and a conductive component, as described earlier. The expression used here is the same as that used in Ref. [5-4] and is due to Kunii [5-10]; for porous materials,

$$k(T) = (1 - \Phi^{2/3})\, k_s + \Phi^{1/3}\,(k_g + \frac{2}{3} h_r D_p) \qquad (5\text{-}50)$$

where $h_r$ is a heat transfer coefficient for radiation,

$$h_r = \varepsilon_T\, 4\sigma T^3, \qquad (5\text{-}51)$$

$D_p$ is the mean pore diameter, $\Phi$ is the total void fraction (including the void space *in* the shreds, and is therefore larger than $\phi$), $\varepsilon_T$ is the emissivity of the shreds, $k_g$ is the thermal conductivity of the gas, and $k_s$ that of the solid shred (and depends on the mass density of the shred).

Also, the diffusion coefficient is assumed to be the same for all the gases; it is given as

$$D_c = D_0(T/273)^{7/4} \qquad (5\text{-}52)$$

where $D_0$ depends on the gas and the background material. Muramatsu gives $D_o$ = 0.112 cm²/sec. Since the gas pressure in the quiescent cigarette is very nearly the ambient pressure, the ideal gas law permits one to write the gas density in the form

$$\rho_g = \rho_{go}(T_o/T) \qquad (5\text{-}53)$$

where T is the absolute temperature.

Finally, expressions for the reaction rates are needed. It is assumed that each is given by an Arrhenius relation; thus

$$R_p = (\rho_T)^m\, Z_p \exp(-E_p/RT) \qquad (5\text{-}54)$$

where the exponent m is to be determined experimentally, as is the "frequency factor" (or "pre-exponential factor") $Z_p$. $E_p$ is the activation energy for the pyrolytic reaction, and R is the universal gas constant. The tobacco density $\rho_T$ may be expressed as

$$\rho_T = \rho_S y_T \qquad (5\text{-}55)$$

where $y_T$ is the tobacco mass fraction.

Similarly, the char-oxidation reaction rate is taken to be

$$R_{co} = \rho_c^{\,n}\, \rho_{o2}^{\,p}\, Z_{co} \exp(-E_{co}/RT) \qquad (5\text{-}56)$$

where (again) the exponents n and p are to be determined experimentally, and the densities are written in terms of the respective mass fractions,

$$\rho_c = \rho_s\, y_c \qquad \text{and} \qquad \rho_{o2} = \rho_g y \qquad (5\text{-}57)$$

The initial conditions are (before ignition of the cigarette)

$$\left.\begin{aligned} \rho_S(x,r,0) &\equiv \rho_{so} = \rho_{To} \\ \rho_C(x,r,0) &= \rho_A(x,r,0) = 0 \\ T(x,r,0) &= T_o \\ y(x,r,0) &= y_a\ (\equiv y_{ambient} = 0.232) \end{aligned}\right. \qquad (5\text{-}58)$$

The boundary conditions are:

on the axis,

$$\left(\frac{\partial y}{\partial r}\right)_{r=0} = \left(\frac{\partial T}{\partial r}\right)_{r=0} = 0 \text{ for all x and t.} \qquad (5\text{-}59)$$

At the lit end of the cigarette, the temperature boundary condition is

$$x = 0 \rightarrow k\left(\frac{\partial T}{\partial x}\right)_{x=0} = \varepsilon_A \sigma (T^4 - T_a^4) + h_c(T - T_a) \qquad (5\text{-}60)$$

for all r and t. $T \equiv T(0,r,t)$ and $T_a \equiv T_{ambient}$.

Here, too, $h_c$ = convective heat transfer coefficient (at the end), $\sigma$ is the Stefan-Boltzmann constant, and $\varepsilon_A$ = emissivity of the cigarette at the x=0 end (we are assuming a grey body — i.e., no wavelength dependence). The value to be used here should be that of the *ash*. Here, we are assuming that the ash never falls off the cigarette — a realistic assumption for the case when the cigarette rests on a substrate, but not realistic for free-air burning; however, this simplifying assumption will probably be adequate. Moreover, if it were not made, the geometry would be continually changing, and the boundary conditions would become exceedingly complicated.

There is usually a filter at the other end. However, this (again) is of minor importance for the cases examined here;[2] thus, for the temperature boundary condition at the other end,

$$x = L \rightarrow -k\left(\frac{\partial T}{\partial x}\right)_{x=L} = \varepsilon_T \sigma (T^4 - T_a^4) + h_c(T - T_a) \qquad (5\text{-}61)$$

for all r and t (where now $T = T(L,r,t)$).

Next, the oxygen boundary conditions must be considered. It is assumed, for the sake of simplicity, that the filter prevents any oxygen diffusion at the cold end[2] (x = L):

$$D\left(\frac{\partial y}{\partial x}\right)_{x=L} = 0 \qquad (5\text{-}62)$$

where D is the diffusion coefficient for oxygen within the cigarette. At the other end, the conditions must be

[2] *The filter is shown in Section 3 to have a substantial impact on ignitions that happen only after the full length of the cigarette is burned; for such cases this boundary condition would have to be changed.*

[3] *Also referred to as $k_g$, by Muramatsu.*

$$D\left(\frac{\partial y}{\partial x}\right)_{x=0} = \gamma_b(y_a - y_c) \quad (5\text{-}63)$$

where $y_c \equiv y(0,r,t)$ is the oxygen mass fraction at the "hot" end of the cigarette and $y_a$ is the ambient fraction, defined in Eq. (5-58). D is a function of temperature; for the sake of simplicity, it is assumed that it is the same function for ash as it is for virgin tobacco and for char. $\gamma$ is the mass transfer coefficient.[3] Muramatsu [5-5] gives it as

$$\gamma_b = 6.38 \times 10^{-3} \left[\frac{T^{2.75}(T-T_a)\,(T+123.6)}{R\,T_a}\right]^{1/4} \text{cm/sec,} \quad (5\text{-}64)$$

for the effect of the boundary layer, where T is the mean value between $T_c$ (the local cigarette surface temperature) and $T_a$ (the ambient temperature), all temperatures in Kelvins.

Finally, the cigarette's side surface must be considered. It is covered by paper; the paper wrapper in principle should also be included with its own set of equations, which will include its reaction kinetics. However, the amount of energy released when it burns is negligible in comparison to that released by the tobacco. If a unique paper decomposition (or ignition) temperature can also be specified, then the paper (kinetic) equations can be replaced by (two) appropriate boundary conditions. This simplifies the problem considerably, though it may omit some potentially interesting physics.

If there were no paper, then the temperature boundary condition at the sides would be

$$-k(x,R)\left(\frac{\partial T}{\partial r}\right)_{r=R} = \varepsilon_c(x)\sigma(T^4 - T_a^4) + h(T - T_a) \quad (5\text{-}65)$$

The emissivity of the cylinder surface will depend on whether it has turned to ash, is still pyrolyzing, or still virgin tobacco; therefore the emissivity has been explicitly shown to be a function of x. Also, the thermal conductivity at the surface will in general depend on whether it is ash, char, or virgin tobacco. The assumption which is made here is that k is the same for all three (assumption #13).

Similarly, although the heat transfer coefficient at the sides, h, will be different from what is at the ends, we simplify by assuming that

$$h_e = h \quad (5\text{-}66)$$

The emissivity $\varepsilon_c$ has one value for the virgin tobacco region, another for the char region, and a third for the ash region. However, these refer to "char" and "ash" *for the paper,* and may occur at different temperatures, and therefore different locations, than for the tobacco. That is, conditions must be chosen for $\varepsilon_c(x)$. The simplest approximation that can be made is that the paper pyrolyzes/ignites/ disappears at some paper ignition temperature $T_{ip}$. Then there are just two values for $\varepsilon_c$ — that for the virgin paper, and that of ash. These meet at the paper burn "line." Experiments have shown (see Figure 5-2) that

$$T_{ip} \simeq 450 \pm 100°C$$

For oxygen, the equation is the analogue of Eq. (5-63):

$$D\left(\frac{\partial y}{\partial r}\right)_R = \begin{cases} \gamma(y_a - y_s) & x \geq x_p \\ \gamma_b(y_a - y_s) & x < x_p \end{cases} \quad (5\text{-}67)$$

where $x_p = x_p(t)$ is the position of the paper burn line at time t.

The paper resistance to oxygen diffusion can be expressed as

$$\gamma_p = D_p/\delta$$

where $D_p$ is the diffusion coefficient in the paper and $\delta$ is the mean paper thickness. The total resistance of both paper and boundary layer is then

$$\gamma = (\gamma_b^{-1} + \gamma_p^{-1})^{-1} \quad (5\text{-}68)$$

Eqs. (5-67) express the simplification that where the paper has burned, its remains present no barrier at all, and the radial oxygen diffusion at the boundary depends only on the properties of the boundary layer.

Thus for the "ideal" model, there are the nine coupled nonlinear PDE'S (36), (39), (42), (43), (48), (49), (53), (54), and (56), in terms of the nine unknowns $\rho_C$, $\rho_g$, $\rho_S$, $\rho_T$, y, T, $u_r$, $R_p$, and $R_{co}$.

### Partial Model

The model outlined above is quite complex; it was therefore decided to consider a subset of the equations which still contains much of the essential physics, but which is more tractable.

### Equations

The simplifications that were made are the following: first, it was assumed that $\rho_g$ = constant and $\rho_S$ = constant. A one-step reaction was assumed — i.e., no pyrolysis, just tobacco oxidation. Thus, $R_p = 0$. It was assumed, (as by Summerfield *et al.* [5-3]), that the char-oxidation reaction is second order — that is, linear in both oxygen and tobacco; i.e., that $n = p = 1$ in Eq. (5-56). Finally, the radiation losses at the boundary were linearized, so that an effective heat transfer coefficient which is the sum of the convective part and the linearized radiative part was used. That is,

$$h(T - T_a) + \varepsilon_c\sigma(T^4 - T_a^4) \rightarrow h'(T - T_a) \quad (5\text{-}69)$$

where

$$h' \equiv h + \varepsilon_c\sigma(\bar{T}+T_a)(\bar{T}^2+T_a^2)$$

$\bar{T}$ being some appropriate average of the surface temperature. The value used by us is given in Table A-1 (Appendix 5B).

Eqs. (5-49) and (5-48), the diffusion equations for temperature and oxygen, simplify to

$$(1-\phi)\rho_s C_s \frac{\partial T}{\partial t} + \phi\rho_g u_r C_g \frac{\partial T}{\partial r} = k\,\nabla^2 T + (1-\phi)\,Q_{co}\,R_{co} \tag{5-70}$$

and

$$\frac{\partial y}{\partial t} + u_r\frac{\partial y}{\partial r} = D_e\nabla^2 y - \frac{(1-\phi)}{\phi\,\rho_g}[n_{o2} + y(1-n_A)]R_{co} \tag{5-71}$$

where $$\nabla^2 \equiv \frac{\partial^2}{\partial x^2} + \frac{\partial}{r\partial r}\left(r\frac{\partial}{\partial r}\right) \tag{5-72}$$

The char-oxidation source term (5-56) becomes

$$R_{co} = \rho_c\rho_g y Z_{co}\exp(-E_{co}/RT) \quad \text{g/cm}^3\text{ sec} \tag{5-73}$$

The approximation $\rho_g$ = const has two immediate consequences:

1. In order to get a given reaction rate, the oxygen concentration must be (incorrectly) calculated to be smaller than it really is, at any temperature higher than ambient.

2. The radial outflow velocities $u_r$ will be calculated to be smaller than they really are. This in turn results in easier inward diffusion of oxygen from the surface, and somewhat smaller convective energy loss.

In the one-step approximation, the equation for $\rho_T(t)$ disappears: each gram of tobacco is replaced by $n_c$ grams of char, and Eq. (5-43) becomes

$$\frac{\partial\rho_c}{\partial t} = -R_{co} \tag{5-74}$$

Muramatsu [5-5] found that a best fit to the data was obtained with p = ½ in Eq. (5-56). Therefore, one version of the program was written using that dependence; that version has had difficulties in converging, however, and so this attempted improvement was dropped.

Eq. (5-39) simplifies to

$$\phi\frac{\partial\rho_g}{\partial t} + \frac{\phi}{r}\frac{\partial}{\partial r}(\rho g u_r r) = (1-\phi)(1-n_A)R_{co} \tag{5-75}$$

As long as $\rho_g$ = const, the first term on the left hand side of Eq. (5-75) vanishes. The velocity $u_r$ is valuable as a check on the program, since it is a sensitive marker of the local reaction rate. This permitted "tuning" the model parameters (many of which could not be obtained from direct measurement).

Thus, this simplified model has four equations for the four variables $\rho_C$, y, T, and $u_r$. It was felt prudent to insert global balance checks for heat and oxygen. These take the form

$$\frac{\partial}{\partial t}\iiint \phi\rho_g y\,dV = \iint \gamma(y_a - y_s)\,dS - \iint \rho_g y u_r\,dS - n_{O2}\iiint (1-\phi)\,R_{co}\,dV \tag{5-76}$$

and

$$\frac{\partial}{\partial t}\iiint [(1-\phi)\rho_S C_S + \phi\rho_g C_g]\,T\,dV = -\iint h'(T_c - T_a)\,dS - \iint \rho_g u_r C_g T_g\,dS + \iiint (1-\phi)\,Q_{co}\,R_{co}\,dV \tag{5-77}$$

where the integrations are over the entire surface and volume of the cigarette. The second term in the left hand side integral of Eq. (5-77) can be dropped, since $\rho_g$ is constant and $\rho_g \ll \rho_s$. Also, consider the middle term on the right hand side of Eq. (5-77): we note that the ideal gas law permits us to write $\rho_g T_g = \rho_a T_a$, in the integrand. (When a pyrolytic reaction is introduced, terms involving $R_p$ will have to appear in the last integrals of Eqs. (5-76) and (5-77)). Insertion of these global checks was very useful in uncovering a number of theretofore-unexpected errors.

The computer program which implements the solution of these four equations is called CIG25.

**Numerics**

These equations were approximated by a set of difference equations for numerical solution; three-point central difference formulas have been used for the spatial derivatives.

The reaction rate is a very sensitive function of temperature, and therefore it follows that the differential equations are "stiff" — i.e. there is a wide variation in reaction rates. This means that very short time steps would be required in the numerical integration of the equations, if an explicit technique were used. In order to permit longer time steps while maintaining stability, therefore, an implicit solution method was used. After a number of other choices proved inadequate (partly because of the complicated boundary conditions), the Crank-Nicolson method was settled on. Since it is an implicit method, some method has to be used to converge to the correct solution. One of the things that was learned during the development of the program is that the oxygen diffusion rate is one to two orders of magnitude faster than the temperature diffusion rate. Therefore one can "decouple" the equations for oxygen and heat diffusion. That is, they can be solved by an iterative procedure of successive approximations, starting with oxygen diffusion. The Gauss-Seidel successive substitution technique was used for both the y and T equations, with a relaxation parameter. That is, the value to be used for variable y after the ith iteration yields $y_i$, is

$$y = (1-\lambda)\, y_{i-1} + \lambda\, y_i. \tag{5-78}$$

Numerical experiments showed that for this subset of equations, a sharp peak of efficiency occurs with $\lambda = 0.9$ (i.e., under-relaxation).[4]

### Initial Conditions

Two sets of initial conditions have been used. First, rather than using Eqs. (5-58), it was assumed that a match had been applied to the x=0 end of the cigarette, producing some reactions; these used up only a small amount of tobacco, but most of the oxygen that had been *in situ*. The initial temperature distribution was assumed to be very high at the tip, then linearly decreasing to ambient temperature. The oxygen mass fraction behaves in complementary fashion.

For the numerical calculations, the cigarette was divided into ten cylindrical shells, i.e., $\Delta r = 0.4$ mm, and into slices of the same thickness, $\Delta x = \Delta r$. The temperature at node n is as given in Col. 2 of Table 5-1.

If we assume that the combustion of char proceeds according to

$$C + \frac{(1+a)}{2} O_2 \rightarrow a\, CO_2 + (1-a)CO,$$

it is clear that 16(1+a)/12 grams of oxygen are needed to burn one gram of carbon (char). It follows that if combustion lowers the local mass fraction of oxygen from $y_a$ to y, it will lower the relative density of char (and hence tobacco) from 1 to x, where

$$x = 1 - \frac{3}{4(1+a)n_c}\left(\frac{\rho_g}{\rho_T}\right)(y_a - y)$$

Therefore, when the initial oxygen distribution is taken to be as given in Col. 3 of Table 5-1, the resulting relative density of tobacco is given in Col. 4 (to three significant figures). $\rho_o$ is the actual mean tobacco density in the virgin cigarette. It became clear during the development of the program that it would be desirable to also have an alternative set of starting conditions. This second set is described later.

[4]*Many of the numerical techniques mentioned here are discussed in Ref. [5-13].*

### Comments

During the development of this model, we have confirmed what has already been known for some time, both from experiment and from earlier modeling efforts; to wit, that the rate at which oxygen is allowed to diffuse into the cigarette is the principal determiner of the burning rate. So that if a "fire-safe" cigarette is wanted, without any other consideration (e.g., flavor, tar and nicotine toxicity of products, etc), one need merely use a paper with marginal permeability—e.g., 4 Coresta units—and this will just about guarantee that the cigarette will go out when dropped on upholstered furniture.

Because this is only a "partial" model, we would expect the results obtained with the current values of input parameters to be somewhat unrealistic. The input parameters therefore have to be modified, in order to (partially) compensate for this. The parameter values used in the calculation are given in Appendix 5-B.

The results obtained with CIG25 are given later, and are there seen to be at least semi-quantitatively reasonable. Nevertheless, there are a number of additions which would improve the accuracy of the model. These are:

1. Introduction of the ideal gas law (Eq. (5-53)),
2. Inclusion of the radiation loss at the boundaries,
3. Inclusion of a pyrolysis reaction,
4. Use of the nonlinear dependence on y, for $R_{co}$.

Beyond these, it would be desirable to take some more physics into account, such as:

5. Inclusion of axial gas flow,
6. Inclusion of the evolution of $H_2O$ vapor and its recondensation downstream,
7. Possibly, the paper kinetics,
8. More than one pyrolytic and/or char-oxidation reaction.

## Table 5-1. First Choice of Initial Distributions of Temperatures, Oxygen Mass Fraction, and (Relative) Tobacco Density, Assumed for the Calculation

**T is in degrees Kelvin.**

| n | T | y | $\rho_{To}/\rho_o$ |
|---|---|---|---|
| 1 | 1000 | .01 | .999 |
| 2 | 1000 | .01 | .999 |
| 3 | 1000 | .01 | .999 |
| 4 | 1000 | .01 | .999 |
| 5 | 1000 | .01 | .999 |
| 6 | 860 | .02 | .999 |
| 7 | 720 | .04 | .999 |
| 8 | 580 | .08 | .999 |
| 9 | 440 | .16 | 1.000 |
| 10 | 300 | .232 | 1.000 |
| . | . | . | . |
| . | . | . | . |
| . | . | . | . |

# Interactions Between Cigarette and Substrate

In this section the effects which take place when the lit cigarette and the substrate are in intimate contact are outlined. Since the principal effect of the cigarette is to heat the substrate, how to find the heat flux from the cigarette to the substrate (when the cigarette has already been influenced by the substrate) is then considered in detail. Finally, the effects of the cigarette on the substrate are touched on.

As we have seen, the substrate is a fairly complicated system, and the cigarette a more complicated one still. The situation when the two are in contact is describable by a still more complex set of equations; we have not attempted to set those up for solution. Instead, let us consider the probable effect of each on the other, in a qualitative way. First, consider the effects of a cigarette on a horizontal substrate, in order of importance. The principal effect is the heating by a hot spot; the cigarette also affects the boundary conditions: it interferes with convective cooling, over its entire length. Moreover, if any oxidative reaction takes place in the substrate, the cigarette "competes" with the substrate for oxygen. Finally, some of the water vapor and tar which are emitted by the cigarette may recondense on the surface of the substrate, and change its thermal characteristics.

The effects of the horizontal substrate on the cigarette are the mirror image of the above, in a sense: first, the cold substrate initially provides a substantial extra heat sink (by conduction). As it heats up, the magnitude of this sink declines. Second, the convective and radiative heat losses are reduced as well. Moreover, this effect varies with time, as the substrate heats up. If the substrate begins to have exothermic reactions, it may change from a *heat sink* to a *heat source*. (The results quoted in Section 4 indicate that this probably will not be the case before ignition, however). Finally, it is evident that just from the geometry, the substrate interferes with the uptake of oxygen by the cigarette. Moreover, if the substrate begins to react with oxygen, then the oxygen depletion for the cigarette would become still more severe.

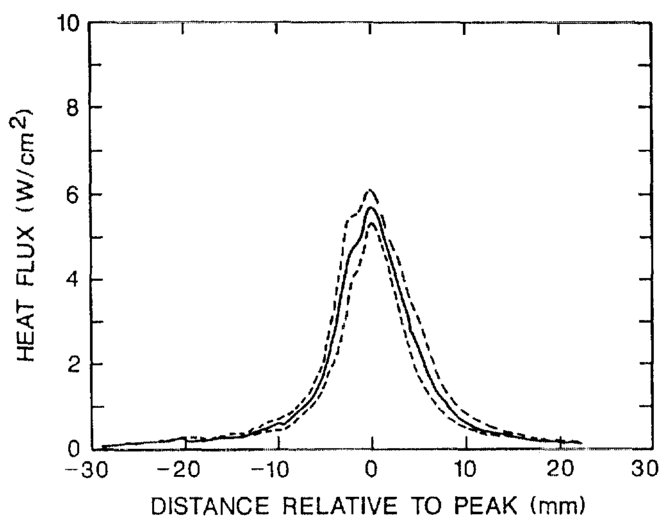
In accordance with the above lists, we begin by calculating the heating flux delivered to the substrate by the *influenced* cigarette.

## Conduction Flux to Substrate

First consider the flux to the substrate. The flux from the various cigarettes was measured with a small, water-cooled flux gauge (see Section 4). The face of the flux sensor (thermopile) was placed flat against the surface of the cigarette, either in free space or flush with the surface of a substrate. The gauge is moved back and forth past the hot region several times; sufficiently slowly that the gauge comes to equilibrium, but fast enough that the cold gauge does not lower the cigarette temperature very much (the typical temperature depression is indeed only momentary, and of about 50–70°C—see Section 4). The heat transfer from the cigarette surface to the sensor is given by

$$\phi \simeq \varepsilon_c \sigma (T_c^4 - T_s^4) + h(T_c - T_s), \qquad (5\text{-}79)$$

**Figure 5-7. Average of Several Measurements of the Flux Emitted by Cigarette 105 Toward the Substrate, Along the Contact Line.** **The Substrate in this Case was Laundered California Fabric 2045, with Foam Padding. The Dashed Curves Indicate the Probable Errors. This Distribution Corresponds to the Temperature Distribution Shown in Figure 5-4.**



where $T_c$ is the cigarette surface temperature, $T_s$ that of the sensor, $\varepsilon_c$ is the emissivity of the cigarette surface, and h is an effective heat transfer coefficient. The second term corresponds to conduction through a thin air space between the cigarette and gauge surfaces. Thus

$$h = k/\delta, \tag{5-80}$$

where k is the thermal conductivity of air at $T = (T_c + T_s)/2$, and $\delta$ is the mean spacing. A typical result is shown in Figure 5-7, corresponding to the temperature distribution shown in Figure 5-4, for cigarette 105. The measured flux is the *initial* (and momentary) flux from the cigarette to the cold substrate at the (very small!) area of contact between them.

How is one to use or interpret this result? If the substrate starts out cold, and is in good thermal contact with the cigarette, this flux represents the *initial* heat flux to it, along the line of contact (LC). It is interesting to see what the *total* energy loss rate is; the flux $\phi(x)$ shown in Figure 5-7 was first integrated numerically, and yielded

$$\int_0^L \phi(x)dx = 6.07 \begin{matrix} +1.17 \\ -0.90 \end{matrix} \quad \text{W/cm.}$$

With this large flux, the substrate heats up rapidly, so that the net flux, given by Eq. (5-79), falls rapidly to lower values.

The flux distribution $\phi(x)$ is that along the line of contact; i.e., it is $\phi(x,0)$; the transverse dependence must also be known. Moreover, we must know $\phi(x,y)$ as a function of time. The latter is in fact readily found, if it is assumed that the cigarette surface temperature profile stays (relatively) constant. For then the flux given by Eq. (5-79) holds at all times; i.e.,

$$\phi(x,t) = \varepsilon_c\sigma[T_c^4(x,t) - T_s^4(x,t)] + h[T_c(x,t) - T_s(x,t)],$$

just as given in Eqs. (5-2) and (5-3) (assuming also that h is constant). That is, we use

$$\phi_o(x,t) = \varepsilon_c\sigma[T_c^4(x,t) - T_a^4] + h[T_c(x,t) - T_a] \tag{5-81}$$

as the source flux for the substrate program, and the *net* heat flux from cigarette to substrate (along CL) is

$$\phi(x,t) = \phi_o(x,t) - \phi_s(x,t), \tag{5-82}$$

where

$$\phi_s(x,t) = \varepsilon_c\sigma[T_s^4(x,t) - T_a^4] + h[T_s(x,t) - T_a]. \tag{5-83}$$

(It has been assumed that the initial substrate surface temperature is the ambient temperature – i.e., $T_s(x,0) = T_a$). $\phi_o(x,t)$ is given by experiment, as in Figure 5-7, and $\phi_s(x,t)$ is calculated by the substrate program.

The conductive flux distribution $\dot{q}''(x,y,t)$ in the transverse direction is calculated in Appendix 5D. The (approximate) expression

$$\dot{q}''(0,y,0) \simeq \dot{q}'(0,0,0)\frac{a^2}{a^2+y^2} \tag{5-84}$$

is derived there, where $\dot{q}'(0,0,0)$ is the (peak) conduction flux on the axis; this flux drops rapidly with time. The parameter a is determined *via* Eqs. (5D-8) and (5D-9); it is of the order R/2. The total conductive loss (at t = 0) is then found to be

$$\dot{E}_{cd}(0) \simeq 2a(\tan^{-1}\xi/a)\int_0^L \dot{q}''(x,0,0)dx,$$

where $\xi$ is another characteristic distance for which a reasonable value is $\xi \simeq R$. With a peak initial flux of 5.6 $W/cm^2$ to the substrate, of which 1.9 $W/cm^2$ is radiative and 3.7 is conductive (see Appendix 5D), we find that for R = 0.4 cm, a = 0.226 cm; then $\xi = R$ implies $\dot{E}_{cd}(0) \simeq$ 2.1 watts as an estimate for the initial energy transfer to the substrate *via* conduction.

Experimental measurements (see Section 4) have shown that the flux from a cigarette can be (very crudely) fitted with a distribution of the form (5-5). If expanded as a power series, this evidently agrees with Eq. (5-84), to lowest order in $y^2$. The total energy output from the distribution (5-5) is

$$\dot{E} = \iint \phi(x,y)dxdy = \pi\sigma_x\sigma_y\phi_m \tag{5-85}$$

Reasonable agreement with experiment is obtained with $\sigma_x$ = 0.6 cm; also, $\sigma_y \geq$ 0.32 cm. For the conductive part, however, we must modify these values to $\sigma_{xc}$ = 0.67 and $\sigma_{yc}$ = 0.30. Then with $\phi_m$ = 3.7 $W/cm^2$, $\dot{E}_{cd}$ is found to be

$$\dot{E}_{cd}(0) \simeq \pi(.67)(.30)3.7 = 2.3 \text{ watts.}$$

With time, this energy loss term must fall according to

$$\dot{E}_{cd}(t) \simeq \dot{E}_{cd}(0)\left[\frac{\bar{T}_c - \bar{T}_s(t)}{\bar{T}_c - T_a}\right] \tag{5-86}$$

where $\bar{T}_c$ is the mean cigarette surface temperature and $\bar{T}_s(t)$ the (rapidly rising) mean surface temperature. In Appendix 5D it is shown that we can use the peak (rather than the average) temperatures in Eq. (5-86):

$$\dot{E}_{cd}(t) \simeq \dot{E}_{cd}(0)\left[\frac{T_p - T_s(t)}{T_p - T_a}\right] \tag{5-86a}$$

The temperature difference $T_p - T_s$ in the steady state is such that

$$\dot{E}_{cd}(\infty) \simeq 0.7 \text{ Watts}$$

## Radiation Flux to the Substrate

Assume an infinite cylinder of uniform temperature $T_c$ resting on the flat substrate. For some area of the substrate of temperature $T_s$, the net radiative flux going into the substrate is

$$\phi_{is} = \varepsilon_s[\Omega\,\phi_c + (1-\Omega)\phi_a - \sigma T_s^4] \tag{5-87}$$

where $\varepsilon_s$ = emissivity/absorptivity of the substrate (assumed constant)
$\phi_c$ = radiation flux from cigarette
$\phi_a$ = ambient radiation flux = $\sigma T_a^4$

and $\Omega$ is the fraction of energy emitted by the given substrate area which would be intercepted by the cylinder. If $\varepsilon_s = \varepsilon_c = 1$, then Eq. (5-87) becomes

$$\phi_{is} = \Omega\,\sigma T_c^4 + (1-\Omega)\phi_a - \sigma T_s^4$$

More generally, an expression for $\phi_c$ is written, and then one solves simultaneously for $\phi_c$ and $\phi_s$. The result is that the flux from the cigarette, $\phi_c$, is given by

$$\phi_c = \varepsilon_c\sigma T_c^4 + (1-\varepsilon_c)\phi_a + \frac{1-\varepsilon_c}{\pi R}\int_0^\infty dx\ \Omega(x)\{\varepsilon_s\sigma T_s^4(x) + (1-\varepsilon_s)[\Omega(x)\phi_c + (1-\Omega)\phi_a]\} \tag{5-88}$$

The configuration (view) factor $F_{sc} \equiv \Omega$ must then be found. From Sparrow and Cess [5.11], we find that for an infinitesimally thin but infinitely long strip on the substrate, parallel to the cylinder axis and a distance y from it, the view factor is

$$\Omega(y) = \frac{R^2}{R^2+y^2} \tag{5-89}$$

where R is the cylinder radius. All but one of the integrals in Eq. (5-88) can now be carried out exactly, and

$$\phi_c\Delta = \varepsilon_c\sigma T_c^4 + (1-\varepsilon_c) \times \left[\left(\frac{5-\varepsilon_s}{4}\right)\phi_a + \frac{\varepsilon_s}{\pi R}\int_0^\infty \Omega(x)\,\sigma T_s^4(x)\,dx\right] \tag{5-90}$$

where $\varepsilon_c$ is the emissivity/absorptivity of the cylinder, and

$$\Delta \equiv 1 - (1-\varepsilon_c)(1-\varepsilon_s)/4 \tag{5-91}$$

There are two interesting cases:

I. Initially, $T_s(y) = T_a$
II. In the steady state, a reasonable approximation to $T_s(y)$ is

$$\sigma T_s^4(y) \simeq \phi_m \frac{R^2}{R^2+y^2} \tag{5-92}$$

where

$$\phi_m = \sigma T_s^4(0) \tag{5-93}$$

is the maximum surface black-body emission. Carrying out the integration in Eq. (5-90), the last integral takes on the values

$$\frac{\varepsilon_s}{\pi R}\int_0^\infty \ldots dx = \begin{cases} \varepsilon_s\,\phi_a/2 \\ \varepsilon_s\,\phi_m/4 \end{cases} \tag{5-94}$$

respectively. These are then to be used in the expression for $\phi_c$, Eq. (5-90), and that in turn is to be used in Eq. (5-87), for the flux (locally) absorbed by the substrate.

From Eqs. (5-87) and (5-89), it can be seen that the radiation flux from the cigarette to the substrate has precisely the same functional form as the conductive flux distribution, Eq. (5-84). Thus our theoretical expression for the transverse dependence of heat flux is

$$\phi(y) \simeq \phi_{co}\frac{a^4}{a^2+y^2} + \phi_{ro}\frac{R^2}{R^2+y^2}, \tag{5-95}$$

where $\phi_{co}$ and $\phi_{ro}$ are the (initial) peak convective and radiative fluxes.

To sum up: an explicit expression for the transverse dependence of the cigarette flux [Eq. (5-95)] has been found, which supplements the generic longitudinal dependence given by Eq. (5-81). Thus, if the longitudinal dependence at the cigarette surface is known, the flux $\phi(x,y)$ can be found by substituting the radiative part of Eq. (5-81) for $\phi_{ro}$ and the conductive part for $\phi_{co}$, in Eq. (5-95).

## Connection with the Semi-Empirical Model

Alternatively, we may consider the above calculations to give a theoretical justification for using a Gaussian as a lowest-order approximation to the transverse dependence of the heating flux. When the example values found above for $\phi_{co}$, $\phi_{ro}$ and a are used in Eq. (5-95), it is found that

$$\phi(R)/\phi(0) \simeq 0.30.$$

This corresponds to using

$$\sigma_y \simeq R/1.1 \simeq 0.36 \text{ cm}.$$

As can be seen from Figure 5-7, the longitudinal dependence of the heating flux also appears to be Gaussian (to lowest order), as has been observed earlier. Thus, Eq. (5-5) should be a fair approximation to the cigarette flux, and it can be used as input for the substrate-heating program. However, $\sigma_x$ and $\sigma_y$ are then needed. Note that $\sigma_y$ can be expected to be proportional to R, simply from geometry.

Since $\sigma_y$ = 0.36 cm for the cigarette of 2.5 cm circumference,

$$\sigma_y = 0.36 \left[ \frac{2\pi R}{2.5} \right] \approx 0.905 \text{ R cm} \qquad (5\text{-}96)$$

in general. For the $2\pi R$ = 2.1 cm cigarette, this yields $\sigma_y$ = 0.30 cm, in good agreement with the value estimated in Appendix 5D. From the correlation between smolder velocity and coal length given by Eq. (5-35), the value of $\sigma_x$ can be connected with the cigarette parameters because $\sigma_x$ should be proportional to $\ell_c$. Using the data available from cigarette 105, one finds: v = 0.668 cm/min, $\ell_c$ = 6.5 ± 0.5 mm, $\rho$ = 0.16 g/cm³, and C = 21 mm. In Appendix 5D, it is shown that $\sigma_x$ = 0.62 ± 0.1 cm. Then

$$\sigma_x = F \rho C v \qquad (5\text{-}97)$$

with F = 165 ± 27 cm² sec/g.

The semi-empirical model and the correlation described above can now be used explicitly. Thus, suppose that the packing density for a particular cigarette is $\rho$ = 0.259 g/cm³, that C = 2.5 cm, and that all but one of the other parameters for this cigarette also have their base (reference) values; but that its diffusion coefficient for oxygen is 10% greater than the reference value: $D/D_o$ = 1.1. Then Eq. (5-17) implies that the smolder velocity is

$$v \approx 0.435 \text{ cm/min} \approx 7.25 \times 10^{-3} \text{ cm/sec},$$

and Eq. (5-97) yields

$$\sigma_x \approx 165\ (0.259)\ 2.5\ (7.25 \times 10^{-3}) = 0.77 \text{ cm}.$$

Similarly, the transverse width of the distribution is given by Eq. (5-96):

$$\sigma_y = 0.36 \left( \frac{2.5}{2.5} \right) = 0.36 \text{ cm}.$$

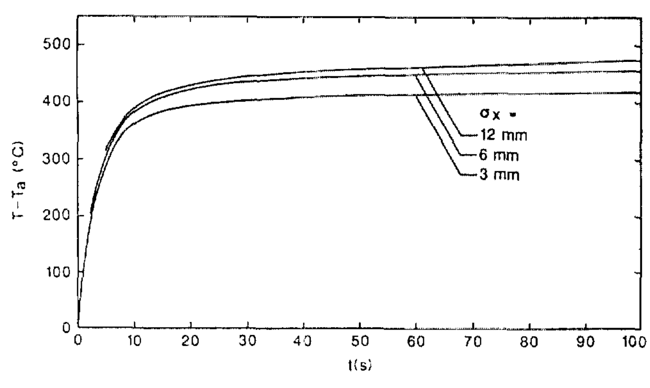
These can now be used, along with $\phi_m$ = 5.6 W/cm², in Eq. (5-5). Later it is shown (see Figure (5-8)) that the peak temperature reached by a substrate, $T_{hi}$, is only weakly dependent on $\sigma_x$ or $\sigma_y$: an increase in $\sigma_x$ leads to a (small) increase in $T_{hi}$, for a given velocity. On the other hand, the increase in $\sigma_x$ here is due to an increase in velocity (over the base value). But a higher velocity means that the total energy injected into the substrate, in a given time, is reduced, and one would expect that to lead to a *decrease* in $T_{hi}$. Indeed, a separate calculation has shown that for the $\sigma_x$ = 3 mm case plotted in Figure 5-8, a velocity v = 4 × $10^{-3}$ cm/sec leads to $T_{hi} - T_a$ = 425.7°C, while a fourfold increase to v = 16 x $10^{-3}$ cm/sec leads to $T_{hi} - T_a$ = 402.2°C. Thus these two effects on $T_{hi}$ very nearly cancel each other. This is rather startling; it seems to suggest that all cigarettes would produce the same peak surface temperature $T_{hi}$, and therefore have the same ignition propensity; whereas as seen in Section 3, this is not at all the case: it was shown there that the expanded-tobacco cigarettes produce fewer ignitions. In fact, our semi-empirical model does indeed predict the same result: suppose that the reference cigarette (v = 0.334 cm/min, $\rho_p$ = 0.259 g/cm³) is once again used, and consider the effect of expanding the tobacco leaf. This lowers the bulk density of the cigarette; if it is lowered by 39%, to $\rho$ = 0.158 g/cm³, then according to Eq. (5-12), the smoldering velocity jumps to v = 0.548 cm/min. At the same time, the axial length of the flux distribution, according to Eq. (5-97), is entirely unchanged, in view of Eq. (5-12). For reasons which will become apparent momentarily, $\phi_p$ was taken to be 5.76 W/cm² for the reference case, rather than 5.60 W/cm². The substrate program then shows that for the calcium silicate substrate, $T_{hi}$ = 489.3°C for the reference case. For the cigarette with expanded tobacco and the same flux, $T_{hi}$ = 483.9°C. Thus if 483.9 < $T_{ig}$ < 489.3°C (and if there were no fluctuations in properties), there would be no ignitions with the "expanded" cigarettes, and *all* ignitions with the non-expanded cigarettes. This is a very narrow temperature range, however.

We now return to the observation made earlier that there is no obvious dependence of flux on cigarette type. A more careful inspection of Figure 5-5 reveals two correlations; first, it can be seen that the average peak flux from the expanded cigarettes (the second letter in the identifying labels is E) is 5.46 W/cm², while for the non-expanded ones (the second letter is N), it is 5.76 W/cm²; this is why the flux was taken to be 5.76 rather than 5.60 W/cm², above. This also suggests a density dependence for the peak fluxes. When the peak fluxes are plotted against the bulk densities, a crude correlation can in fact be established, though the scatter is very large. If the two worst outliers are omitted, the following relationship is found by linear regression:

$$\phi_p \approx 4.982 + 3.085\ \rho_p \text{ W/cm}^2 \qquad (5\text{-}97a)$$

The correlation coefficient is r = 0.54. A second observation is that the Burley cigarettes (identified with B as the first letter) averaged $\phi_B \approx$ 5.85 W/cm², while the cigarettes made with flue-cured tobacco (identified with F as the first letter) averaged $\phi_F \approx$ 5.29 W/cm². Indeed, a least-squares fit was made to the data for the two sets of cigarettes, and it was found that

**Figure 5-8. Peak Temperatures of the Calcium Silicate Substrate Surface as a Function of Time, for the Flux Used for Cigarette 105, for Several Values of $\sigma_x$**



$$\phi_F(n) = 4.95 + 0.0336\ n\ W/cm^2 \qquad (5\text{-}97b)$$

$$\phi_B(n) = 5.53 + 0.0316\ n\ W/cm^2, \qquad (5\text{-}97c)$$

where n is the number of ignitions

Consider the second observation first: the fact that the peak fluxes for the Burley cigarettes are, on average, 0.56 $W/cm^2$ greater than for the flue-cured cigarettes, ought to be reflected in a clearly greater ignition propensity for the Burley cigarettes. In fact, it is not (see Section 3). That it is not implies that

(a) The peak heating flux is irrelevant to the ignition process,

or (b) Although the fits for Burley and flue-cured appear to be separate and distinct, the actual separation between them is negligible,

or (c) There are some other factors which compensate for the flux difference.

Aside from the fact that we know (from the equations of physics) that the peak flux *does* play a central role, Eqs. (5-97b) and (5-97c) themselves clearly indicate that the peak flux correlates with ignition. Thus hypothesis (a) must be dropped. Hypothesis (b) is dubious. This leaves us only with (c). There is in fact a difference in the densities of B and F cigarettes, but that difference is minor, and it only accounts for a small part of the 0.56 $W/cm^2$ difference. The rest of the difference remains a puzzle.

One final observation must be made: it is quite remarkable that the slopes in Eqs. (5-97b) and (5-97c) are nearly identical. This is surely not a coincidence. Moreover, with the maximum density of 0.32 $gm/cm^3$ among the cigarettes used in this study, Eq. (5-97a) yields $\phi_p = 5.94\ W/cm^2$. The difference is 0.53 $W/cm^2$, nearly the same as that given by Eqs. (5-97b) or (5-97c) for $\Delta n = 20$. Thus if this density difference corresponded to zero to 20 ignitions, the slope $\partial\phi_p/\partial n$ from Eq. (5-97a) would be nearly the same as that of the other two lines!

Now consider the mean density of the expanded-tobacco cigarette: it is $\rho_p = 0.158\ g/m^3$, and Eq. (5-97a) suggests that the flux to be used should be 5.47, rather than 5.76 $W/cm^2$. Carrying out the substrate-heating calculation again with this lower value of $\phi_p$ yields $T_{hi} = 467.0°C$ — a substantially lower peak temperature. This temperature is sufficiently lower (22°C) than the peak temperature calculated for the non-expanded tobacco (489.3°C) that the results found in Section 3 become entirely understandable. (Except for the lack of difference between Burley and flue-cured).

## Cigarette Energy Balance in the Presence of a Substrate

Next, it is necessary to see how the presence of the substrate affects the cigarette, particularly its energy balance. Two of the principal effects are, loss of energy to the substrate by heat conduction, and reduction of the oxygen supply. Before explicit calculations of the change in energy loss by the cigarette due to the presence of the substrate are made, the following needs to be pointed out: The burning rate is principally controlled by the rate at which oxygen can diffuse into the cigarette, as has been seen earlier. When the cigarette is placed on a substrate, the availability of oxygen declines because of the interference of the substrate with the (air) flow field. Experimental measurements have shown (Section 4) that the decline in burning rate is about 17% (an average over all cigarettes examined on a flat horizontal substrate). The fluctuations about this average value are substantial, however.

If a steady state is achieved, then the rate of production of heat must also decline by 17%, just as the heat loss rate does. We can now make theoretical estimates of the heat losses by the interacting cigarette.

Figure 5-9 is a reproduction of Figure F,6b from Ostrach [5-12]. It shows the calculated streamlines during free convective cooling of a heated horizontal cylinder. It is apparent that at large distances, the flow is *inward;* near the cylinder, it all becomes upward. When a surface is placed under it, the flow is affected substantially: to *zeroth order,* the convective cooling will be diminished by the fact that the flow is eliminated in the lower region (where we now have conductive cooling, instead). Since that is a strip of width $2\xi$, it corresponds to an angular wedge of central angle $2\theta$, where

$$\tan\theta \simeq \xi/r_o;$$

with $\xi = 0.75r_o$, $\theta = 36.9°$, while $\xi = r_o$ yields $\theta = 45°$. $\xi$ might be still larger.

For the infinite, uniform-temperature cylinder in free space, the local heat transfer coefficient $h(\theta)$ decreases monotonically from a broad peak at the lower stagnation point, to zero at the upper one, as shown by Figure 5-10 (Figure F,6a, in Ref. [5-12]. The g(x) in this figure is proportional to $h(\theta)$; the proportionality constant is unimportant). This near-constancy can also be seen in a striking way from Figure 7-4 of Ref. [5-9]. The average h is

$$h = \frac{1}{\pi}\int_0^\pi h(\theta)d\theta,$$

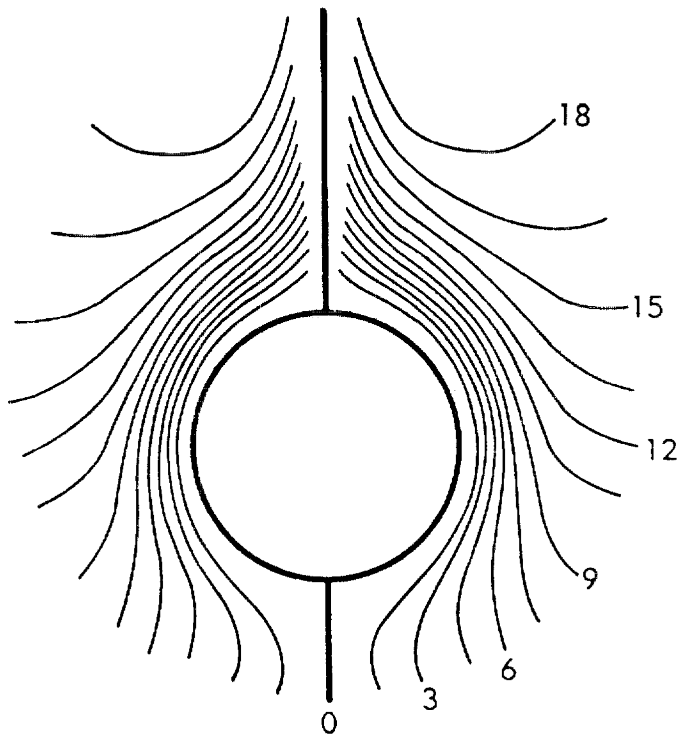
and its value is given by Eq. (5C-4). If $\xi = r_o$ is assumed, the integration should only extend from $\pi/4$ to $\pi$; then the integral is only 69% of the original. Assuming that the convective losses from the cigarette behave in a way similar to those from the constant-temperature infinite cylinder, the convective cooling by air when the cigarette is placed on the substrate is only about 0.7 (or less) of what it is in the open.

One must also ask how the radiative cooling is changed. Without the substrate, the radiative energy loss from a "cigarette" of length L, temperature $T_c$, is

$$\dot{E}_{out} = 2\pi RL\varepsilon_c\sigma T_c^4,$$

while the feedback from the environment is

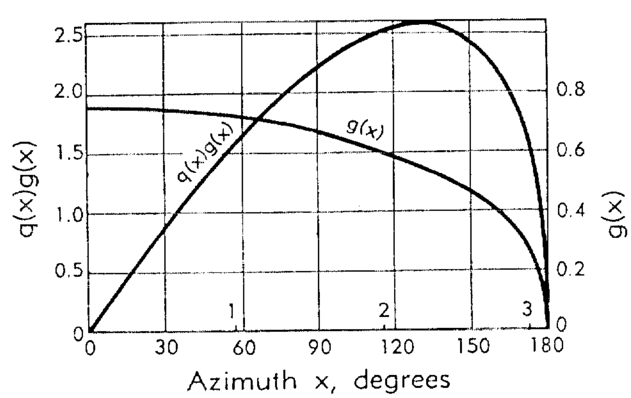
**Figure 5-9. Reproduction of Figure F,6B from ref. [5-12]. Theoretical Streamlines for horizontal cylinder.** The scale is for Gr $=10^4$.




$$\dot{E}_{in} = 2\pi RL\varepsilon_c\sigma T_a^4.$$

With the substrate present, the radiation energy feedback $\dot{E}_{in}$ increases, while the surface temperature decreases, so that the net loss is smaller. It is easy to show that the energy input to the cylinder from the lower half space is

**Figure 5-10. Reproduction of Figure F,6a from ref. [5-12]. Azimuth function g(x) giving variation of local heat transfer coefficient.** The other curve is of no relevance here.




$$\dot{E}_L = 2\,L\varepsilon_c\int_0^\infty dx\Omega(x)[\varepsilon_s\sigma T_s^4(x) + (1-\varepsilon_s)[\Omega\,\phi_c + (1-\Omega)\phi_a]] \quad (5\text{-}98)$$

(where $\phi_c$ is given by Eq. (5-90)). Thus, including the upper half-space,

$$\dot{E}_{in} = \pi RL\varepsilon_c\phi_a + \dot{E}_L \quad (5\text{-}99)$$

The result depends on $T_s(x)$. Two cases are again considered:

Case I: $T_s(x) = T_a$ $(t=0)$

Case II: $T_s(x)$ is given by Eq. (5-92)

For case I, Eq. (5-99) yields

$$\dot{E}_{in} = \frac{\pi R}{2}\,L\,\varepsilon_c[4\,\phi_a + (1-\varepsilon_s)(\phi_c-\phi_a)], \quad (5\text{-}100)$$

while case II yields

$$\dot{E}_{in} = \frac{\pi RL}{2}\,\varepsilon_c[2\varepsilon_s\phi_m + 2\phi_a + (1-\varepsilon_s)(\phi_c+\phi_a)]. \quad (5\text{-}101)$$

The peak value of the substrate temperature will generally be in the neighborhood of its ignition temperature. That is, it is assumed that $T_s(0)$ in Eq. (5-93) is $T_s(0) = T_{ig}$. Ignition temperatures for substrates lie in the range $T_{ig} = 400 \pm 100°C$.

Explicit calculations can now be made in order to find how much the radiation loss is changed, when the cylinder is placed on the surface. The reference values $\varepsilon_c = 0.73$, $\varepsilon_s = 0.8$, $T_a = 27°C$, and $T_{max} = 400°C$ are used. The new peak surface temperature $T_{cs}$ has yet to be determined; assume that

$T_{cs} = T_c = 600°C$. Then

$\phi_a = 0.0459$ W/cm², $\varepsilon_c\sigma T_c^4 = 2.404$ W/cm², Eq. (5-91) implies $\Delta = 0.9865$,

and $\varepsilon_s\phi_m = 0.931$ W/cm²

Then:

Case I $(t=0)$: $\phi_c = 2.455$ W/cm² (only slightly higher than $\varepsilon_c\sigma T_c^4$)

and $\dot{E}_{net}/\dot{E}^o_{net} = 0.963$

Thus, there is a 3.7% decline in net radiation loss (due to reflections from the cold substrate).

Case II (steady state): $\phi_c = 2.456$ W/cm²

and $\dot{E}_{net}/\dot{E}^o_{net} = 0.824$;

that is, the decline in the net radiation loss rate is 18%, "late" in the substrate-heating process.

There is one more effect to be included: when a cigarette is placed on a substrate, its surface temperature distribution changes: its peak temperature drops from $T_c \simeq 600°C$ to $T_p$, and its width along the axis rises from $\sigma_x$ to $\sigma_x'$, in proportion to the increase in the length of the coal from $\ell_c$ to $\ell_c'$. The total energy loss for cigarette 105 smoldering on the substrate is estimated (Appendix 5C) to be $\dot{E} = 3.75$ W and in the open, at a rate 17% higher:

$\dot{E}^o = 3.75/0.83 = 4.52$ watts. It was also found that this is divided into $\dot{E}_c^o \simeq 2.02$ W and $\dot{E}_r^o \simeq 2.49$ W. From the estimates made just above, therefore, when the cigarette is dropped onto the substrate, the convective loss must go from $\dot{E}_c^o$ to

$$\dot{E}_c = 0.69 \left[ \frac{T_p - T_a}{873 - T_a} \right] \frac{\ell_c'}{\ell_c} \dot{E}_c^o,$$

where $T_p$ is the new peak value.

The radiative loss must go from $\dot{E}_r^o$ to

$$\dot{E}_r = \left( \frac{T_p^4 - B/4\sigma}{T_c^4 - T_a^4} \right) \frac{\ell_c'}{\ell_c} \dot{E}_r^o,$$

where $T_c$ is the peak surface temperature while in the air (currently, we take $T_c \simeq 600°C$) and B is the square bracket in Eq. (5-101).

Finally, Eq. (5-86a) is used for the conductive flux. It is then found that a drop of only 10°C, to $T_p = 590°C$, requires a 5% increase in cone length: $\ell_c'/\ell_c = 1.049$) to yield the observed energy loss rate; a drop of 20°C requires a 10% increase ($\ell_c'/\ell_c = 1.105$). Assuming a drop to 580°C, one obtains

$$\dot{E}_r = 2.03, \quad \dot{E}_c = 1.01, \text{ and } \dot{E}_{cd} = 0.71 \text{ watts.}$$

These three values are not very sensitive to the various assumptions made for $T_p$, $T_c$, etc.

## Summary

In this section it has been shown that some reasonable estimates for the reduction in convective and radiative losses of a cigarette when it is dropped on a substrate can be made; for the case under consideration, 50% and 19%, respectively. A reasonable estimate for the additional loss due to conduction to the substrate can also be made: about 0.7 watts. Together, these yield the observed decline of about 17% in the cigarette burning rate.

# Results from Using the Models

The use of the semi-empirical model to find the four parameters needed in Eq. (5-5) for the cigarette flux has already been discussed. In this section the results which are obtained from using the substrate program with a given flux, will first be examined. Then, the results of using the smoldering-cigarette program CIG25 will be examined.

## Substrate Program

It is important to validate the computer model against experiment. The following experiment was carried out:[5] a smoldering cigarette was placed on a porous, low-density calcium silicate insulation block. This material is fairly homogeneous, and is essentially inert, as determined by differential scanning calorimetry (DSC). Two thermocouples were embedded right at the surface, 10 mm apart. The cigarette was placed so that the line connecting the thermocouples was also the line of contact with the substrate, and with the paper burn line about 7 mm from TC #1. A continuous record was made of the temperatures recorded by TC's 1 and 2. The flux distribution that was used was that shown in Figure 5-7, and the values (from the literature) used for $\rho$, C, and k for the calcium silicate were $\rho$ = 216 kg/m³, C = 1.12 J/gm°C, and k = 0.0715 W/m°C. With these inputs, v = 0.5 cm/min = $8.33 \times 10^{-5}$ m/sec, and $\varepsilon_s$ = 0.95, the program gave temperatures considerably higher than the measured temperatures. It was noted that k and C could both be expected to increase with temperature, and so another run was made, using k = 0.10 W/m°C, but keeping $\alpha$ the same (i.e., C was increased to 1.12 (0.1/.0715) = 1.57 J/gm°C). This gave the improved, but still inadequate, results shown on the next page, at t = 84 sec. That is the time at which the paper burn line should have traveled the distance vt = 7 mm, and have been located right above TC #1. This is indicated by the first dash mark in the computer output shown on the next page. The first column indicates the temperature above ambient, along the substrate center line. The second column shows the temperatures at the adjacent mesh points (1.67 mm to the right), and so on. The top row is at zero, because that (vertical) face is kept at ambient (the boundary condition). Thus, the calculated temperature at TC #1, at the moment the peak flux passes over it, is 495.98°C above ambient, or 516°C. Six mesh points below corresponds to the distance 6 × 1.67 = 10 mm, so TC #2 is located there, as is indicated by the second dash mark. The temperature calculated there is 145.88 °C above ambient, or about 166°C. The temperatures *measured* at that moment, by contrast, were 420°C and 54°C, respectively. Two minutes later, the calculated temperatures at TC's nos. 1 and 2 were 167°C and 518°C, respectively, *vs measured* temperatures of 269°C and 413°C. Thus, at t = 84 sec, the calculated temperatures were 96° and 112°C too high; while at 204 sec, they were low by 102°C and high by 105°C, respectively.

Three of the four readings are much lower than the calculated values, and the question is "why?" The "anomaly" at TC #1 at t = 204 sec will be explained presently. There are several possibilities:

a. The substrate contains water (absorbed, or of hydration) which must be driven off.

b. The substrate is not inert, and experiences endothermic pyrolysis.

c. The assumed input flux is too high.

d. The thermophysical values used for the calculation are inaccurate.

e. The program is incorrect.

f. The cigarette produces water and/or tars which condense onto the substrate, acting thereafter as a heat sink.

g. The heat transfer coefficient (for convective cooling of the surface) is larger than assumed.

As for hypothesis (a): the calcium silicate was kept in a dessicator for more than 24 hours before the test. As for (b): as pointed out above, DSC analysis showed that this is not the case.

[5] *This is also described in Section 4, but the redundancy will perhaps be useful here.*

| X LENGTH | Y MESHES | ALPHA | K | H | EMS | DT | TIME | DELTA |
|---|---|---|---|---|---|---|---|---|
| .0667 | 20 | .295E-06 | .07[illegible] | 10.00 | .950 | .200 | 84.000 | .00167 |

| FMAX | VX | SIGX | SIGY | XZRO | SIZE RATIO | EMS LOSS(J.) |
|---|---|---|---|---|---|---|
| 56000.0 | .833E-04 | .00700 | .00360 | .01932 | .33333 | 6.22 |

| # OF STEPS | SUBSTRATE HEAT, JOULES | INTEG. FLUX, JOULES | CONVECT LOSS, JOULES |
|---|---|---|---|
| 420 | 96.33 | 353.79 | 128.77 |

SURFACE TEMPERATURE, (X-Y PLANE), LEFT HALF

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| 2.20 | 2.12 | 1.90 | 1.59 | 1.26 | .93 | .66 | .44 | .28 | .17 |
| 4.89 | 4.71 | 4.20 | 3.50 | 2.73 | 2.02 | 1.41 | .94 | .59 | .36 |
| 8.65 | 8.30 | 7.34 | 6.04 | 4.67 | 3.41 | 2.37 | 1.56 | .98 | .59 |
| 14.32 | 13.65 | 11.91 | 9.63 | 7.32 | 5.27 | 3.61 | 2.36 | 1.47 | .88 |
| 23.19 | 21.93 | 18.73 | 14.77 | 10.96 | 7.74 | 5.22 | 3.37 | 2.08 | 1.23 |
| 37.38 | 34.97 | 29.04 | 22.11 | 15.89 | 10.94 | 7.24 | 4.61 | 2.81 | 1.65 |
| 60.10 | 55.51 | 44.55 | 32.46 | 22.41 | 14.96 | 9.68 | 6.06 | 3.66 | 2.13 |
| 95.33 | 86.91 | 67.24 | 46.67 | 30.72 | 19.78 | 12.48 | 7.67 | 4.57 | 2.63 |
| 145.63 | 131.22 | 98.12 | 65.12 | 40.84 | 25.27 | 15.51 | 9.35 | 5.49 | 3.13 |
| 204.96 | 182.79 | 132.79 | 86.76 | 52.35 | 31.16 | 18.59 | 10.99 | 6.36 | 3.58 |
| 229.54 | 202.05 | 142.87 | 108.22 | 64.61 | 37.14 | 21.50 | 12.44 | 7.09 | 3.94 |
| 305.37 | 267.91 | 186.08 | 136.96 | 78.26 | 42.99 | 24.04 | 13.58 | 7.61 | 4.18 |
| 386.02 | 339.29 | 234.30 | 166.74 | 91.34 | 47.98 | 25.89 | 14.27 | 7.86 | 4.26 |
| 451.49 | 398.00 | 274.75 | 190.93 | 101.18 | 51.15 | 26.71 | 14.37 | 7.79 | 4.17 |
| 490.16 | 432.79 | 298.55 | 204.07 | 105.44 | 51.67 | 26.25 | 13.83 | 7.38 | 3.91 |
| — 495.98 | 437.53 | 300.42 | 202.77 | 102.76 | 49.18 | 24.44 | 12.67 | 6.67 | 3.51 |
| 467.26 | 410.60 | 279.17 | 186.51 | 93.17 | 43.86 | 21.47 | 11.00 | 5.74 | 3.00 |
| 406.68 | 355.04 | 238.05 | 157.86 | 78.16 | 36.50 | 17.73 | 9.03 | 4.69 | 2.44 |
| 322.60 | 279.45 | 184.68 | 122.15 | 60.38 | 28.23 | 13.73 | 6.99 | 3.63 | 1.89 |
| 229.85 | 197.77 | 129.37 | 85.97 | 42.84 | 20.25 | 9.95 | 5.10 | 2.66 | 1.39 |
| — 145.88 | 125.05 | 81.56 | 54.97 | 27.91 | 13.49 | 6.76 | 3.51 | 1.85 | .97 |
| 82.54 | 70.73 | 46.39 | 32.02 | 16.75 | 8.37 | 4.31 | 2.28 | 1.22 | .65 |
| 41.93 | 36.02 | 23.94 | 17.10 | 9.32 | 4.86 | 2.59 | 1.41 | .76 | .41 |
| 19.30 | 16.67 | 11.31 | 8.46 | 4.85 | 2.66 | 1.47 | .82 | .46 | .25 |
| 8.14 | 7.09 | 4.95 | 3.92 | 2.39 | 1.38 | .80 | .46 | .26 | .14 |
| 3.19 | 2.81 | 2.04 | 1.72 | 1.12 | .69 | .42 | .25 | .14 | .08 |
| 1.18 | 1.05 | .80 | .73 | .51 | .33 | .21 | .13 | .07 | .04 |
| .42 | .38 | .31 | .30 | .23 | .15 | .10 | .06 | .04 | .02 |
| .15 | .14 | .12 | .12 | .10 | .07 | .05 | .03 | .02 | .01 |
| .05 | .05 | .05 | .05 | .04 | .03 | .02 | .01 | .01 | .01 |
| .02 | .02 | .02 | .02 | .02 | .01 | .01 | .01 | .00 | .00 |
| .01 | .01 | .01 | .01 | .01 | .01 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |
| .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 | .00 |

An attempt was made to test possibility (c), by changing $\sigma_x$ from 7 mm to 6.1 mm. The results at t = 2, 10, and 84 sec are displayed in Figures 5-11a to 5-11c, in a graphical form. The isotherms at multiples of 50°C are displayed; these make the gradual heating up of the substrate obvious. The movement of the temperature peak, approximately tracking the movement of the flux peak, is also clear. The results, however, are only marginally better than for the previous run.

Next, hypotheses (c) and (f) were tested together, by using a different heat source: a thin, electrically-heated vertical rod, with one end held stationary about 2 mm above the substrate. This heat source produces no water, and the flux from it can be measured unambiguously. The flux is shown in Figures 5-12a and 5-12b, in two orthogonal directions. The average was fitted with a sum of two Gaussian curves such as given by Eq. (5-5), with v = 0. $\sigma_x = \sigma_y$ (the flux must be cylindrically symmetric).

The calculated ($T_{ca1}$) and the measured ($T_{ex1}$) values of the temperature at the surface, at the origin, are given in Cols. 2 and 3 of Table 5-2, respectively. As before, there is a second thermocouple 1 cm from the center; the calculated ($T_{ca2}$) and the experimental ($T_{ex2}$) values are given in Cols. 4 and 5. The errors are still substantial, but only about *half*

**Figure 5-11a. Calculated Isotherms on a Calcium Silicate Surface, Resulting from Heating this Substrate with the Flux Shown in Fig. 5-7 (from Cigarette 105), at Time t = 2 sec.** Solid and dashed curves alternate to facilitate distinguishing among adjacent isotherms.

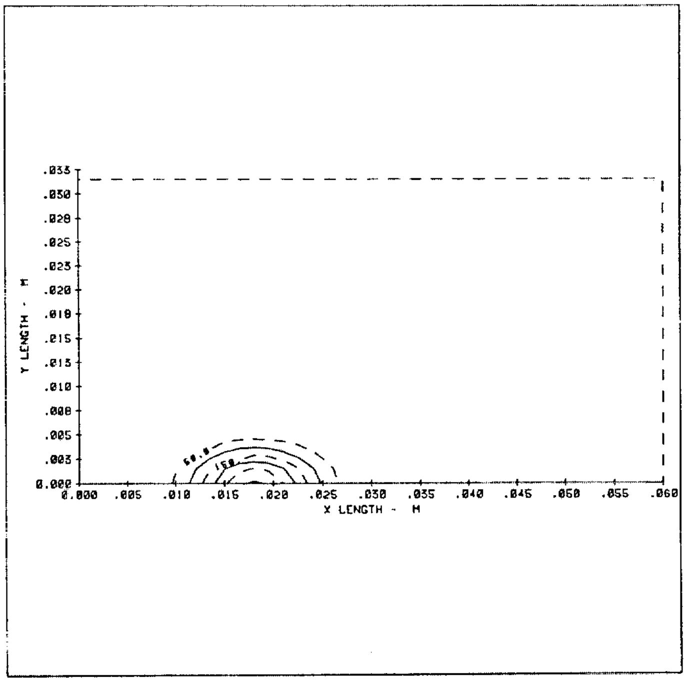
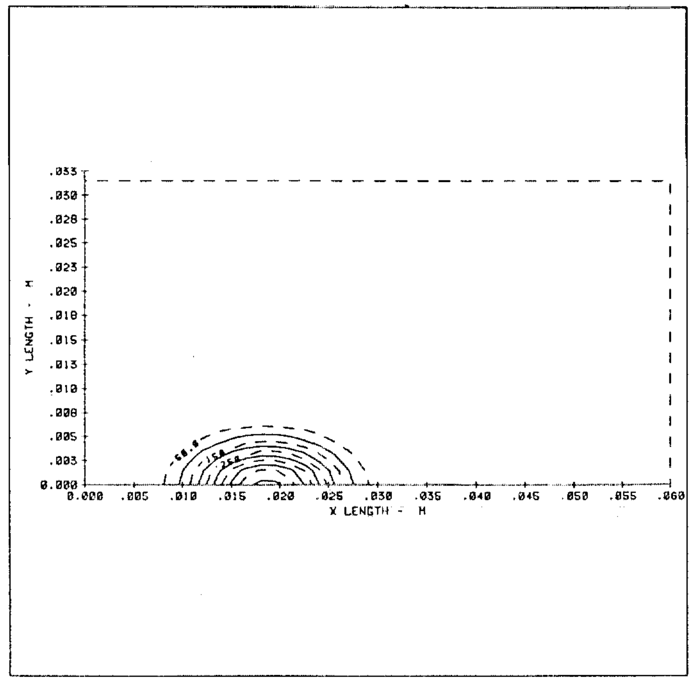



**Figure 5-11b. Calculated Isotherms on a Calcium Silicate Surface, Resulting from Heating this Substrate with the Flux Shown in Figure 5-7 (from Cigarette 105), at Time t = 12 sec.** Solid and dashed curves alternate to facilitate distinguishing among adjacent isotherms.




what they were for the cigarette as a source. If we assume that the program is correct, then the only remaining explanations are (d) and (g): the thermophysical constants used for calcium silicate were incorrect, and/or h is larger than 5.

One can expect that with increasing temperature, k and $C_p$ would both increase. It was found that the experimental results could be reasonably well matched by using k = 0.10 W/m°C, $\rho$ = 205 kg/m³ (the substrate lost 10% of its mass in the D S Calorimeter), $C_p$ = 2.57 J/gm°C, $\varepsilon_s$ = 0.9, and a heat transfer coefficient h = 18 W/m²°C. The resulting calculated values at TC1 and TC2 are shown in Cols. 6 and 7 as $T'_{ca1}$ and $T'_{ca2}$. No choice was found which would yield the experimental value for TC2 at t = 180 sec, while also giving reasonable values for the other thermocouple at other times. The experiment should have been rerun with the heater centered over TC2, in order to test the correctness of the initial experimental run; but there was not enough time to do this.

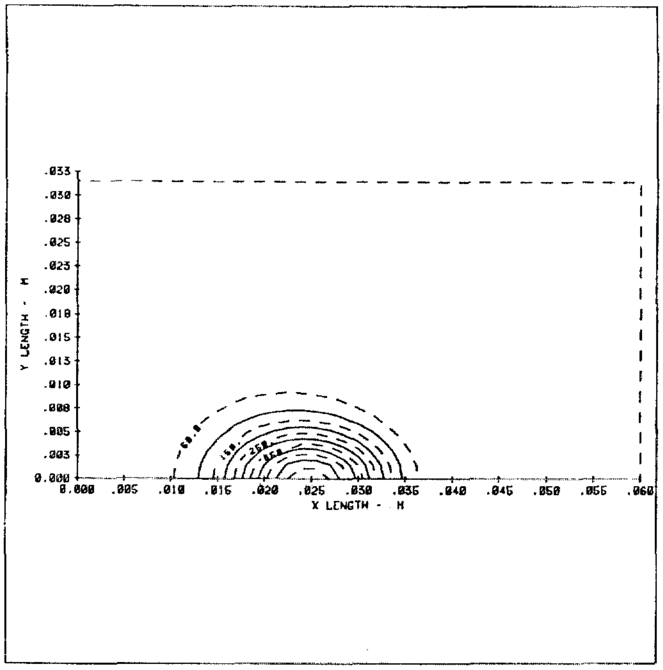
The inadequacy of the literature values of k and $C_p$ to yield the observed results indicates that without adequate input data, the models will not give reliable results.

The program was then rerun, using these effective values of k, $\rho$, $C_p$, etc, for the substrate. For the input flux, that corresponding to cigarette 102 was used: $\sigma_x$ = 6.1 mm, $\sigma_y$ = 3.0 mm, $\phi_m$ = 5.6 W/cm², and v = 0.38 cm/min. The results are shown in Figure 5-13a. As is seen there, the peak temperature read by TC1 is well reproduced, though the calculated temperature rises too quickly at first, and falls too slowly beyond the peak. Similarly, the temperature at TC2 appears to rise too rapidly. The reason for the too-rapid-rise lies in the asymmetry of the input flux: as seen in Figure 5-4, the temperature rise along the cigarette is very rapid at the front end, and elongated behind; the flux must follow the same pattern. Eq. (5-5) prescribes a flux with fore- and aft-symmetry, however, so that the asymmetry cannot be modeled at present.[6] In order to obtain the observed temperature dependence at TC1, therefore, a smaller value of $\sigma_x$ was used: $\sigma_x$ = 4 mm. This choice results in a good fit at TC1, as is seen in Figure 5-13b. The calculated temperature at TC2 lags the measured temperature; presumably, this is because the Gaussian distribution has

**Table 5-2. Calculated and Experimental Values of Temperatures (in degrees C) at TC1 and TC2, as a Function of Time.**

| t(sec) | $T_{ca1}$ | $T_{ex1}$ | $T_{ca2}$ | $T_{ex2}$ | $T'_{ca1}$ | $T'_{ca2}$ |
|---|---|---|---|---|---|---|
| 10.8 | 403 | 298 | 105 | 79 | 296 | 75 |
| 22.8 | 447 | 335 | 136 | 89 | 347 | 95 |
| 82.8 | 486 | 388 | 189 | 113 | 395 | 130 |
| 180 | 497 | 405 | 211 | 126 | 408 | 147 |

**Figure 5-11c. Calculated Isotherms on a Calcium Silicate Surface, Resulting from Heating this Substrate with the Flux Shown in Fig. 5-7 (from Cigarette 105), at Time t = 84 sec.** **Solid and dashed curves alternate to facilitate distinguishing among adjacent isotherms. The flux peak has travelled 7 mm in this time.**

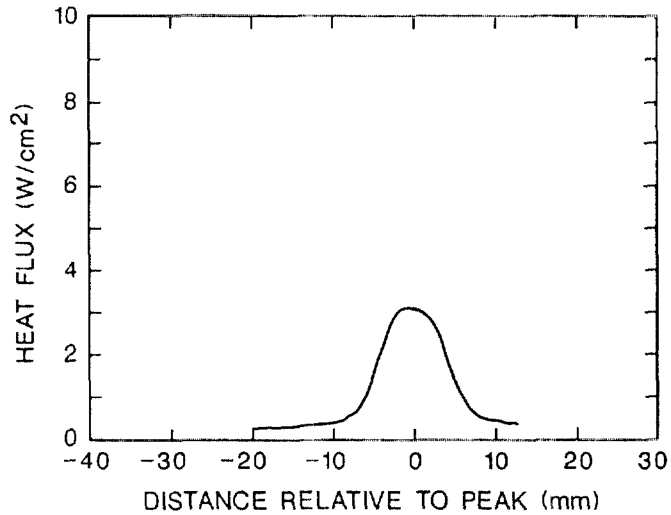



the flux falling off *too* rapidly at large distances. However, this inadequacy is of minor significance for our purposes. The more important fact is that the magnitude of the temperature peak was found, within 14°C.

The paper burn line reached TC1 at t ≃ 95 sec; this is marked point A on the figure. The peak flux arrives 20 sec later; this is marked as point B. At the given burn velocity, this difference corresponds to about 1.3 mm.

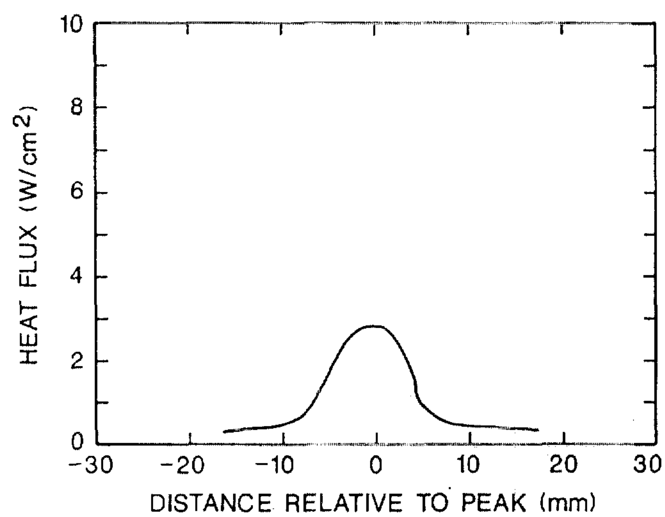
Instead of finding the temperature at a fixed location (such as at a thermocouple), one can ask what the peak surface temperature is at any moment, regardless of where on the substrate it is. If the substrate had an ignition temperature $T_{ig}$, this would permit one to see whether $T_{ig}$ is reached (or exceeded) anywhere. The results for three such runs are shown in Figure 5-8, where the only change from one curve to another was to lengthen the flux distribution (by increasing $\sigma_x$). The peak temperature approaches an asymptotic value fairly rapidly, for each choice. As we might have expected, the asymptote is higher, the larger $\sigma_x$ is, but the affect is relatively small: a 100% increase in the axial length of the distribution (from $\sigma_x$ = 3 mm to 6 mm) produces only an 8.7% increase in the (asymptotic) temperature rise, while a further doubling (to 12 mm) produces only a further 3.8% rise. On the other hand, the asymptotic

**Figure 5-12a. Flux Measured Under the Rod Heater, Along the Substrate**



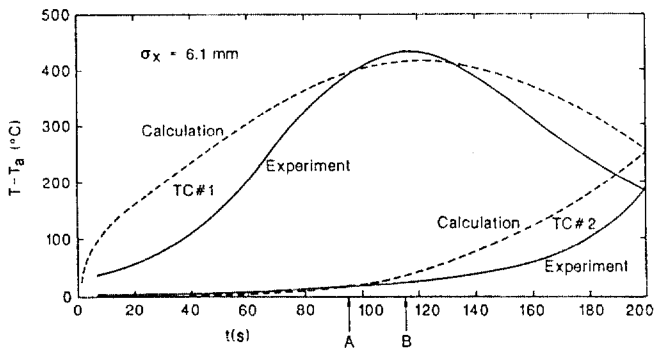

temperature rise, $\Delta T_{max}$, is directly proportional to the peak flux, so that the variations in the peak flux will influence $\Delta T_{max}$ much more strongly. For a given type of cigarette, peak fluxes may vary by as much as 10% from one to another; this would lead to 10% differences in the temperatures developed in the substrate. If the ignition temperature is near the calculated peak temperature, therefore, fluctuations among the cigarettes may lead half the cases to ignite. The same effect can cause the ignition tendency to have an apparently strong dependence on $\sigma_x$ in spite of the weak dependence of $\Delta T_{max}$ shown here; Figure 4-23 implies such an effect. The corollary is that to ensure no ignitions, we must have $\Delta T_{ig}$ be 10% or more above the predicted $\Delta T_{max}$.

**Figure 5-12b. Flux Measured Under the Rod Heater in the Direction Orthogonal to that Traversed in the Measurements Shown in Figure 5-12a**




[6] *The reason for the inadequate fit in Figure 5-14a only became clear during the writing of this report, and there was no time to generalize the input flux.*

**Figure 5-13a. Calculated and Predicted Temperatures at Thermocouples TC1 and TC2 When the Smolder Wave from Cigarette 102 is Made to Pass Over Them.** **The Point A Corresponds to the Paper Burn Line Crossing TC1; Point B Corresponds to the Flux Peak Passing Over It**

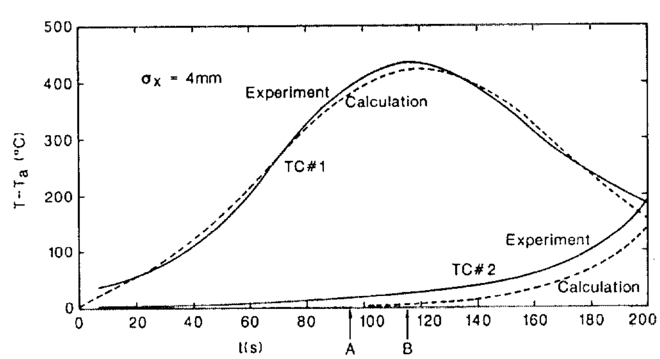



## Cigarette Program

During the development of the program, radial and temporal oscillations were observed in the output, especially for the oxygen results. The cause of the first was (too) large spatial gradients. This was corrected by reducing the mesh size from $\Delta x = \Delta r = 0.04$ cm to $\Delta x = \Delta r = 0.02$ cm. Also, the time step was reduced to 5 ms. Finally, the convergence criterion was tightened from 1% to 0.1%; this gave smoother results and therefore better values for the derivatives.

Some graphical routines have also been incorporated into the program, so that the results can be more readily visualized. The results of running the program, starting with the initial conditions for T(x) given earlier, are shown in Figures 5-14a to 5-14e; the results are shown for t = 0, 2, 4, 6, and 7.86 sec. The results are plotted here as isotherms (with temperatures in degrees Celsius). Contours of constant oxygen mass fraction are also obtainable from the program, but are not given here in the interest of saving space. We note that the peak temperatures occur in a torus which gradually approaches the axis – this is where the reaction rates peak. With time of course the peak temperatures will lie on the axis.

**Fig. 5-13b. Calculated and Predicted Temperatures at Thermocouples TC1 and TC2 When the Smolder Wave from Cigarette 102 is Made to Pass Over Them.** **The Point A Corresponds to the Paper Burn Line Crossing TC1; Point B Corresponds to the Flux Peak Passing Over It. The Flux Distribution Has Been Taken to be Narrower than in Figure 5-13a.**




If the program were permitted to run long enough (30-60 sec), the solution would "relax" to the quasi-steady state. This would have been very costly in computer time, however. Moreover, it would not have been very useful, since it is the (quasi) steady state that is compared with experiment and with other models. Much more sensible, therefore, is to use a starting condition for the cigarette which is already close to a steady (or quasi-steady) state. It is also the condition which prevails when the cigarette is dropped onto furniture. Therefore, an alternative "initial" condition was chosen, which corresponds to the experimentally observed distributions of y and T, shown in Figures 5-2 and 5-3. The approximations to those distributions used here, are shown in Figures 5-15a and 5-16a (corresponding to t = 0). The peculiar appearance of some of the contours in Figure 5-16a is an artifact of the graphical-display computer package: it sometimes connects points which should not be connected. The subsequent figures show the evolution of the distributions in the model "cigarette" with time, out to 18 sec. We note that the temperature diffuses rather more, in this submodel, than it does in reality. That is, the temperature distribution becomes too broad (perhaps because water vaporization has been

**Figure 5-14a. Initial Temperature Distribution (in °C) Chosen for Calculation, to Simulate Effect of Lighting Cigarette With a Match.** **Solid and dashed curves alternate to facilitate distinguishing isotherms.**

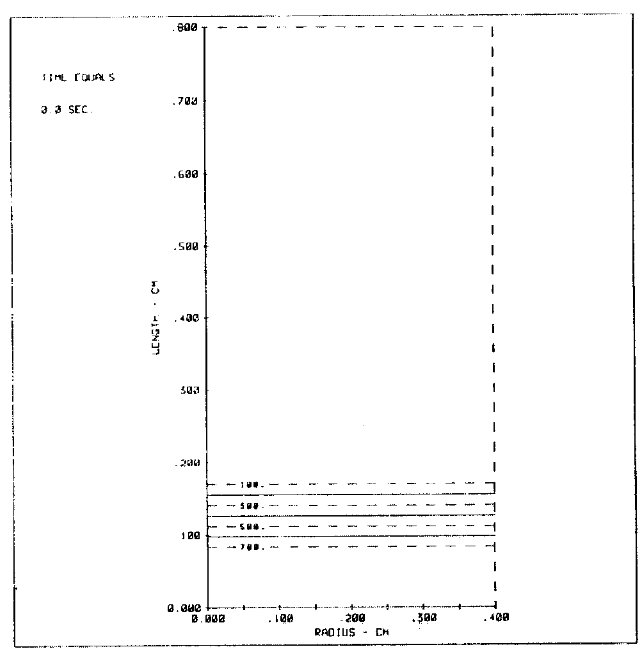


**Figure 5-14b. Isotherms at t=2 sec, after Initiation as in Figure 5-14a**

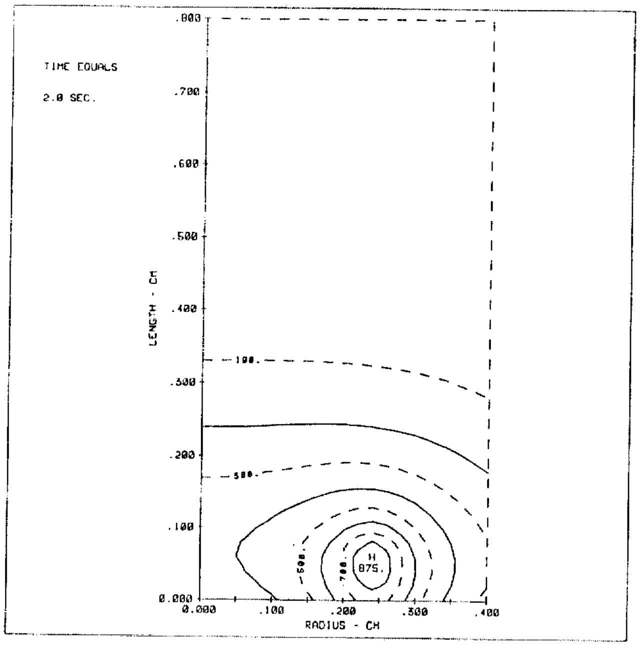
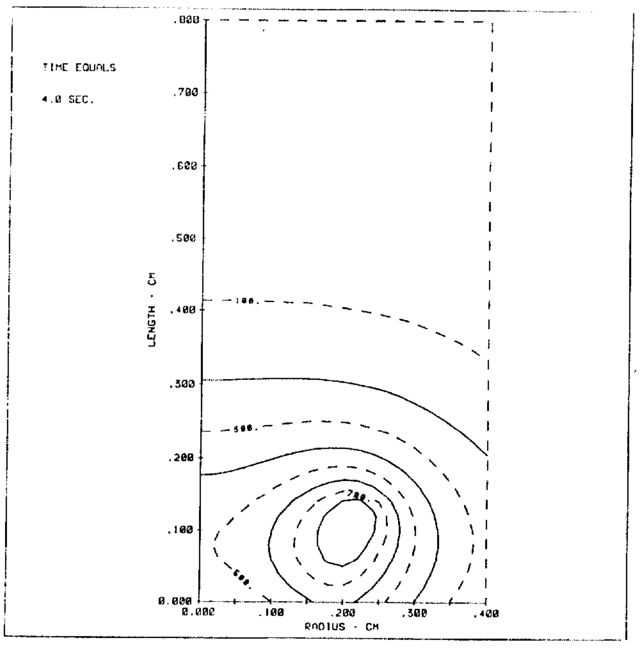



**Figure 5-14c. Isotherms at t=4 sec.**




neglected). This result is the opposite of that obtained with Muramatsu's model, where the temperature distribution is too narrow.

By following the intersections of a specific isotherm on the axis — say, that for 700°C — we readily infer the velocity of the smolder wave. (This can also be done by following the 450°C point on the surface, which is the paper burn line.) We find that for another set of parameters, the velocities (using the 700°C isotherm) vary with t as shown in Figure 5-17. $v_U$ is the velocity of the upper intersection, $v_L$ that of

**Figure 5-14d. Isotherms at t=6 sec.**

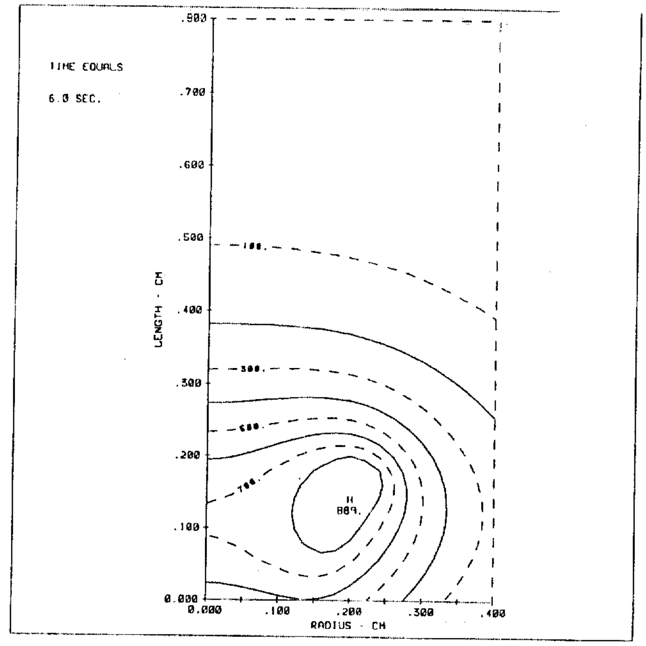
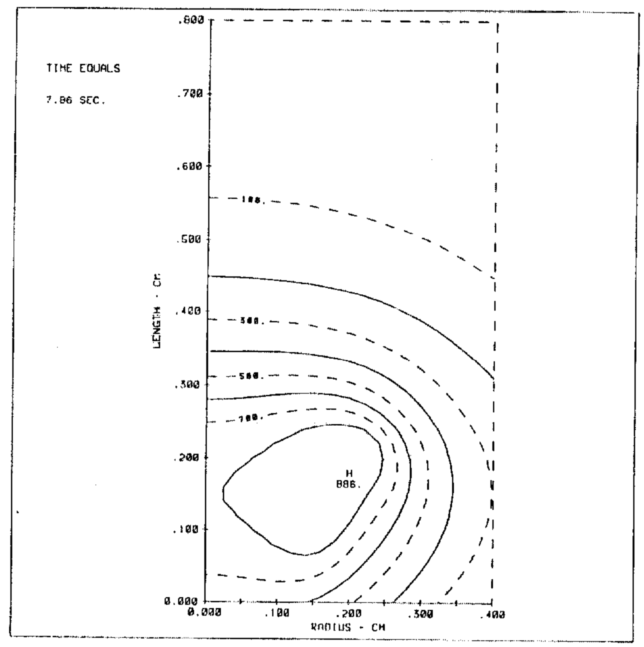



**Figure 5-14e. Isotherms at t=7.86 sec.**




the lower intersection. The smolder velocity may be taken to be the (arithmetic) mean. We see that the velocities drop rapidly to nearly asympotic values. These values are not the same, however, and since $v_L > v_U$ beyond t = 17, the hot zone is apparently shrinking; if this continued, the cigarette would go out. A steady state is obtained with the parameter values shown in Table A1, Appendix 5B.

The peak interior temperatures are on the axis, and are quite reasonable. The peak surface temperatures (at the sides) are of the order of 550°C, essentially what is

**Figure 5-15a. Isotherms for Second Set of Starting Conditions. These were Taken from Figure 5-2.** The reason for alternating solid curves and dashed curves is explained in the captions for Figures 5-11a and 5-14a.

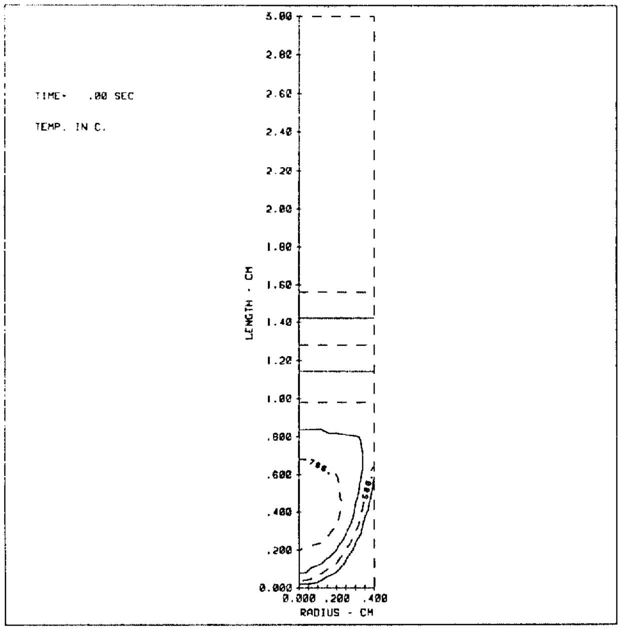
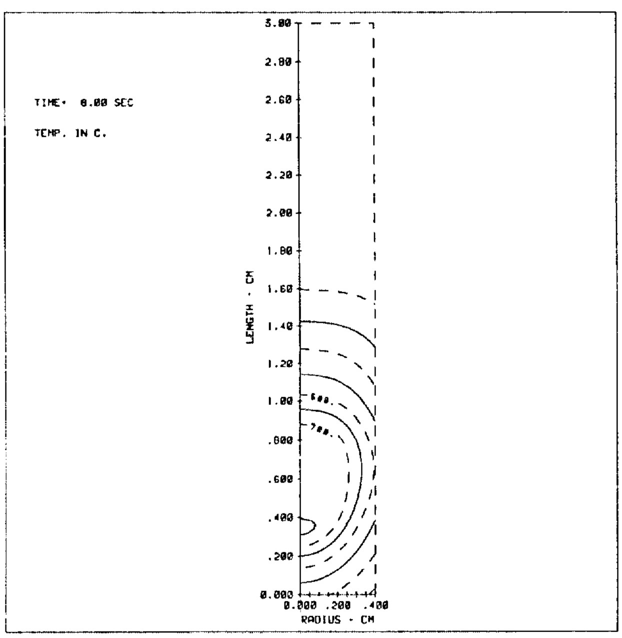



**Figure 5-15b. Isotherms corresponding to smolder wave at t=6 sec.** These result from calculations made with CIG25.




observed. In Figures 5-18a–5-18c, the outflow velocities are plotted, again as contours. It is interesting to note that there are *two* tori with peak rates; presumably one corresponds to a region where the oxygen concentration is relatively high, even though the temperature is not a peak, and the other reaction peak, to a region where the temperature is rela-

**Figure 5-15c. Isotherms in the model cigarette at t=12 sec.**

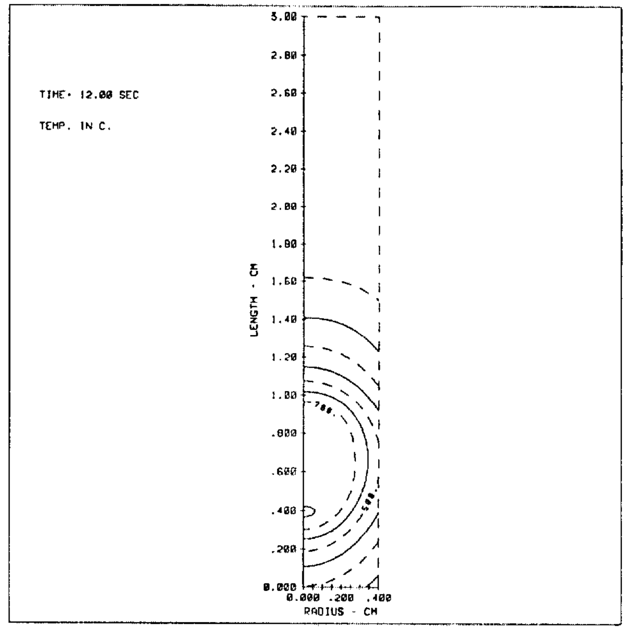
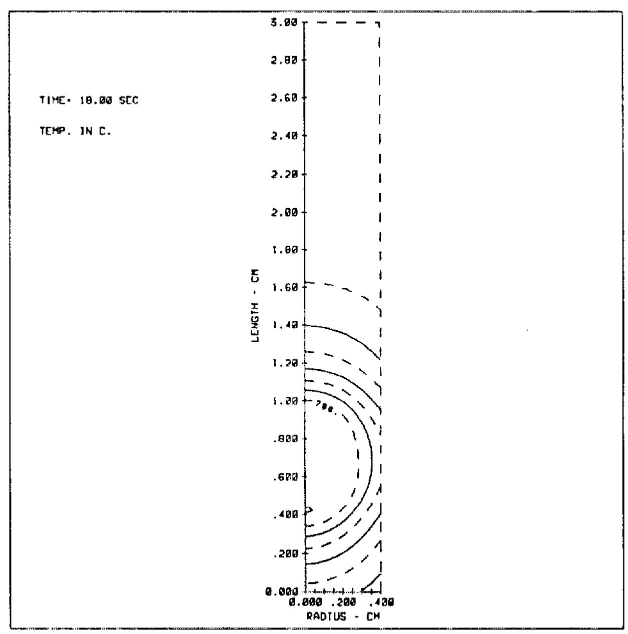



**Figure 5-15d. Isotherms at t=18 sec.**




tively high, although the oxygen is low. This result may be an artifact of CIG25, however; gas outflow from pyrolysis would tend to suppress oxidation behind the coal – i.e., in the upper part of Figure 5-15d.

The results are quite sensitive to the input parameters, especially (of course) the paper permeability. The program runs much more smoothly with the second set of initial conditions, as is evidenced by the much shorter computer time required to make a run of given length. Thus, the "partial" model runs well, and gives results which appear to be reasonable.

**Figure 5-16a. Contours of constant oxygen mass fraction, corresponding to Figure 5-15a (t=0). See the text for discussion.**

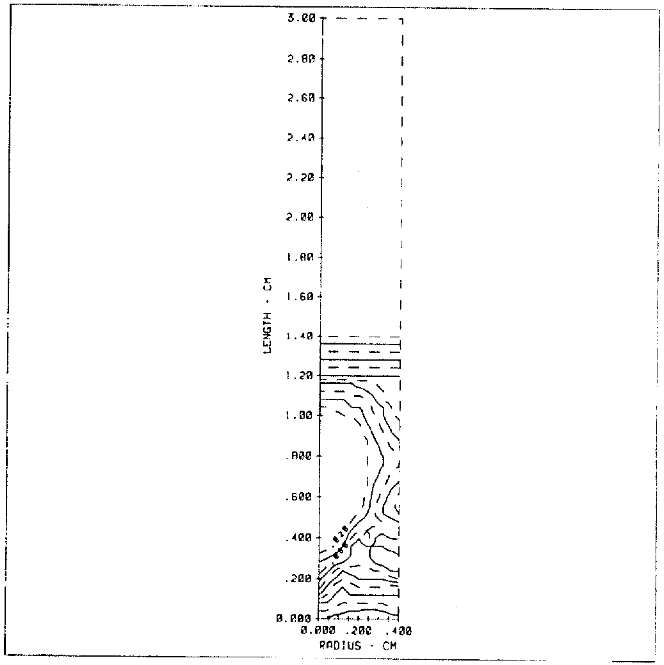



**Figure 5-16b. Oxygen mass fractions at t=6 sec, from the same calculation that yielded Figure 5-15b.**

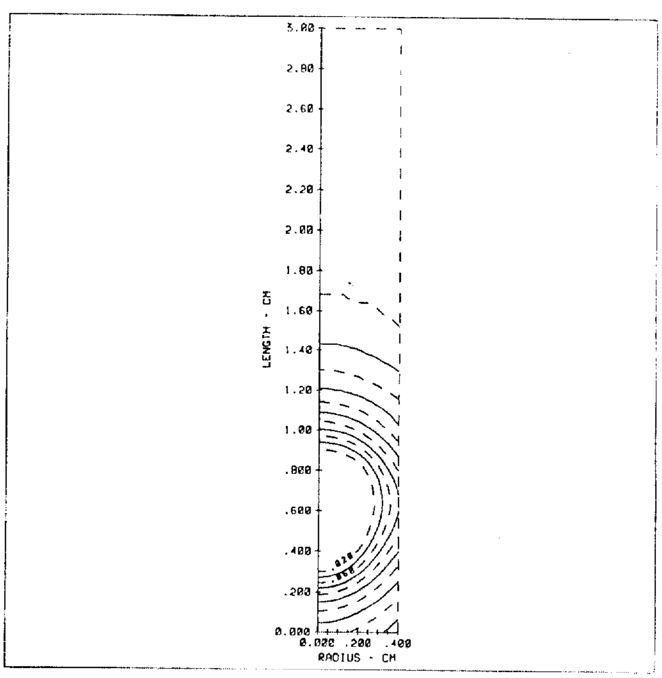



**Figure 5-16c. Oxygen mass fractions at t=12 sec.**

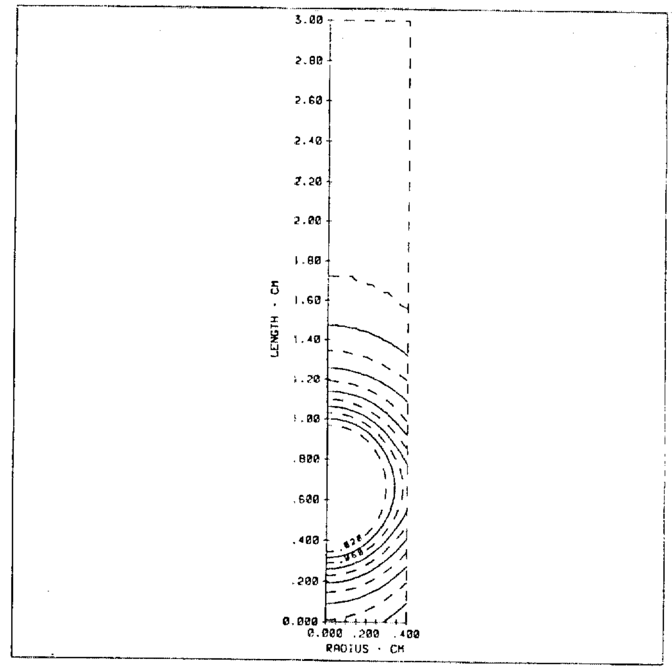



**Figure 5-16d. Oxygen mass fractions at t=18 sec.**

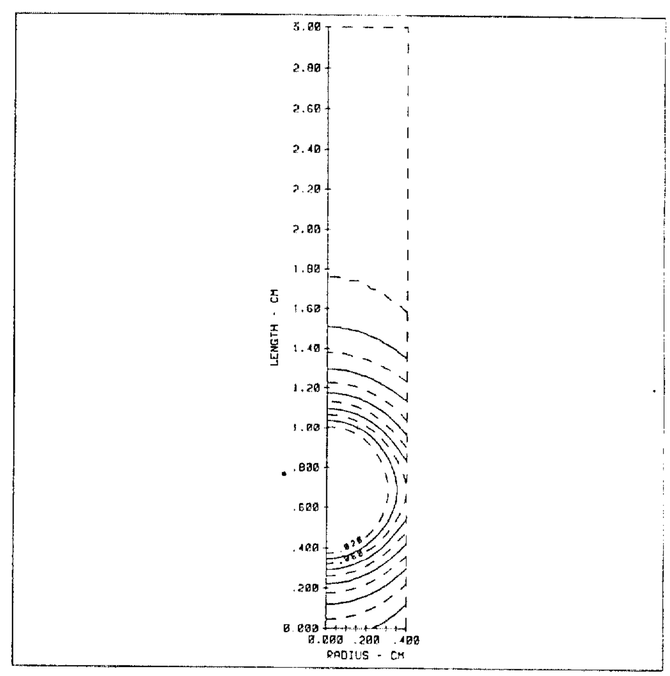


**Figure 5-17. Calculated Velocities of the Upper and Lower Intersections of the 700°C Isotherm with the Axis, as a Function of Time.** These were Obtained by Starting with the Second Set of "Initial" Conditions.

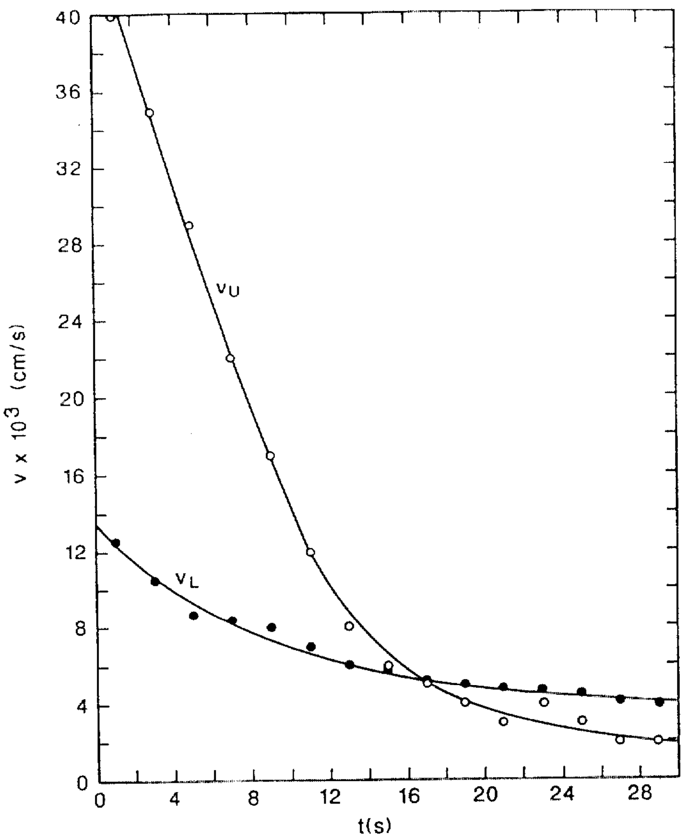



**Figure 5-18a. Contours of constant radial gas velocity at t=6 sec, from the calculation that yielded Figures 5-15b–d and 5-16b–d.**

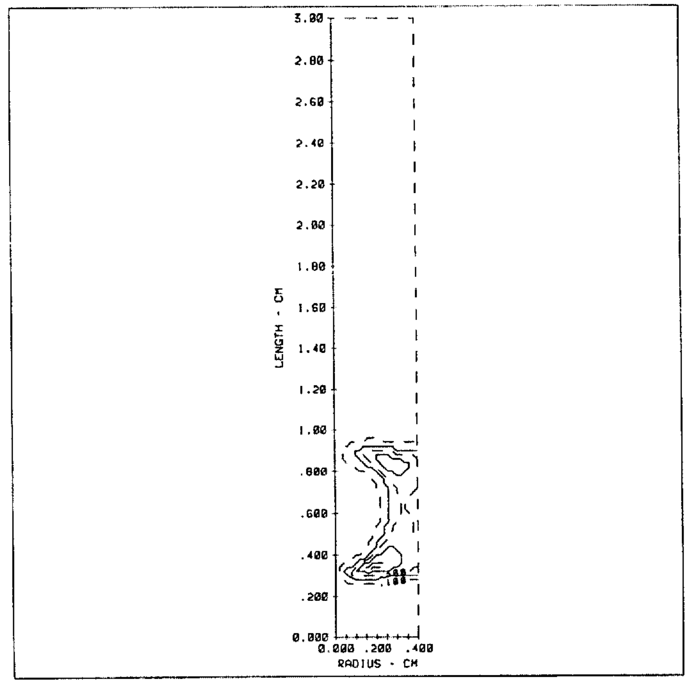



**Figure 5-18b. Contours of constant radial gas velocity at t=12 sec.** The values are in cm/sec.

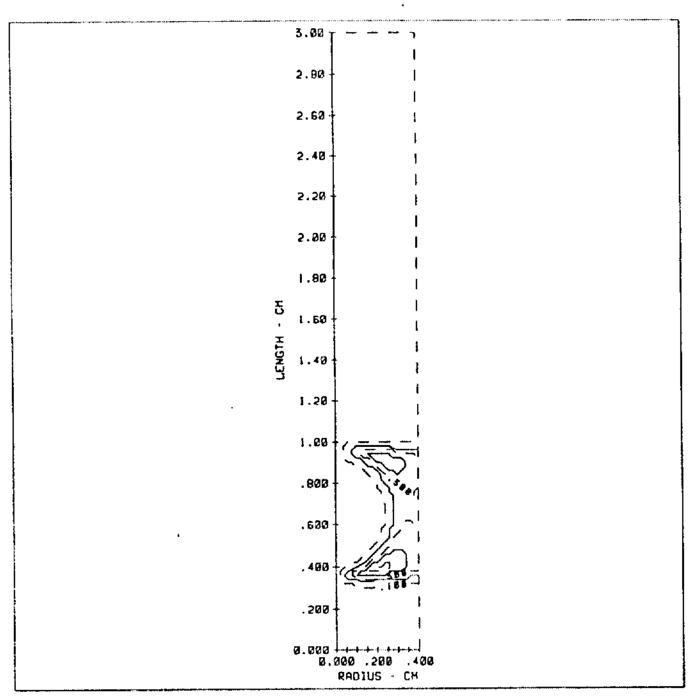
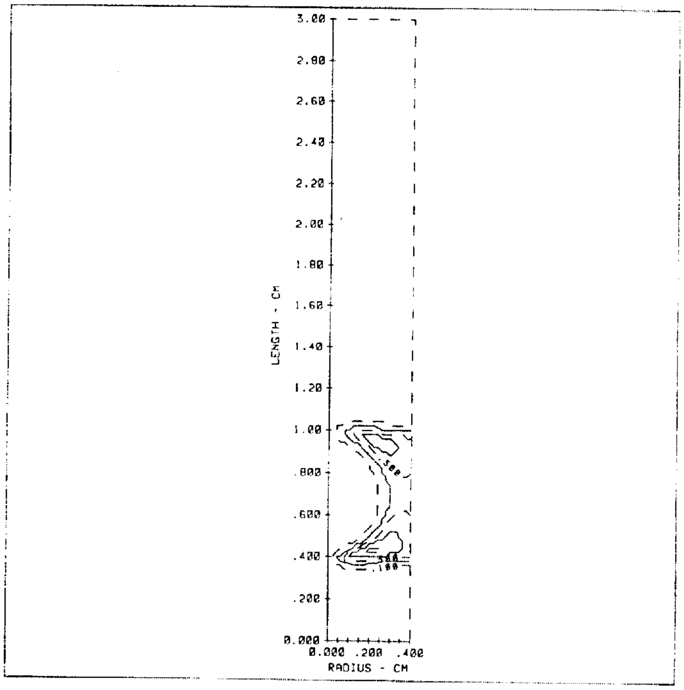


**Figure 5-18c. Contours of constant radial gas velocity at t=18 sec.**



# Summary and Conclusions; Lessons Learned

A smoothly-running computer program (TEMPSUB) has been produced, which yields the temperature distribution in an inert substrate, when subjected to a heating flux. This heating flux is Gaussian with an elliptical cross section, and can be taken to be a moving source (with arbitrary velocity). The peak flux and the widths of the distribution are also user-specified. The program has been checked against known analytic solutions, and has produced answers which are correct (within the limitations of the numerical procedures). When realistic inputs are supplied, it predicts temperatures in good accord with experiment.

A smoothly-running computer program (CIG25) has also been produced, which incorporates a major fraction of the known physical/chemical processes occurring in a naturally-smoldering cigarette, as outlined earlier. This model is an advance over previous models in that it is two dimensional, time-dependent, and takes into account the effects of the paper wrapping on oxygen diffusion. Running this program produces fairly realistic temperature and oxygen-concentration profiles, as well as yielding a realistic smolder velocity.

The key variables which have been identified pertain to oxygen transport: the permeability of the paper to oxygen, the temperature at which the paper burns, and the diffusion coefficient in the tobacco column.

Following an independent line, a semi-quantitative analysis which directly yields the widths of the heating flux distribution from a cigarette smoldering on a substrate has also been carried out. This flux can then be used in the substrate-heating program. The analysis is based on empirical correlations of burning velocity *vs* some cigarette parameters, and on similar correlations based on Muramatsu's model. It also depends on a new correlation developed here. This semi-empirical model works well. The detailed model is potentially even better, but it is (currently) difficult to make the lengthy computer runs needed to carry out parametric studies.

A conclusion of central importance is that the very best substrate and cigarette models are not very useful unless reliable thermophysical data, especially for the substrate, are available. To be sure, if a particular cigarette on a particular substrate does not succeed in igniting it, then the cigarette model will serve to tell us what changes can be made without increasing the ignition propensity on *that* substrate, even with inadequate data. Vice versa, if a cigarette *does* ignite some substrate, the cigarette model will serve to tell us what changes can be made without *lowering* the ignition propensity. But the intermediate cases, which are more interesting, could not then be analyzed.

The problem – i.e., modeling a cigarette, a substrate, and their interactions – is exceedingly complicated. The (sub-)model, as it stands now (CIG25), neglects some non-negligible aspects of the physics – such as axial flow, the gas continuity equation, the ideal gas law, pyrolysis, the production and transport of water, radiation loss at the boundary, a more complete paper model, etc. Nevertheless, it is already sufficiently realistic that it can manifest a number of the features of cigarette behavior, including realistic temperature and oxygen-concentration profiles, realistic velocities for the thermal wave, etc. For example, if one wants to lower the smoldering rate of a cigarette, one can:

a. Decrease the permeability of the paper, as already pointed out above,

b. Increase the heat transfer rate at the surface (this could be done by increasing the emissivity of the paper, for example),

c. Increase the tobacco packing density (see Eq. (5-12)).

In fact, almost every parameter affects v. Items a–c are, of course, qualitatively obvious; but the model permits quantification of these effects.

Note that decreasing the smoldering velocity of a cigarette *without making any other changes in its properties* (not possible, of course!) would increase the ignition propensity However, decreasing the smoldering velocity also decreases the length of the coal; the combined effects are to slightly *lower* the ignition propensity. If the decrease in velocity results from an increase in packing density, then there is an accompanying increase in peak heat flux to the substrate, which increases the ignition propensity more dramatically. These results agree with the experimental findings in Section 3.

As pointed out in the introduction, a good mathematical model permits one to not only interpolate properly between experimental results, but also to extrapolate to new situa-



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tions. Thus the model can also allow one to investigate the effects of changing other parameters which may be amenable to control in industrial production, and which have important impacts on smoldering, such as changing the void fraction $\phi$ (and thereby the packing density), changing the tobacco type (which would affect the reaction kinetics, and therefore the rate, directly), changing the cigarette radius, etc. Much of this is also obtainable from Muramatsu's model; those results are given by Eqs. (5-6) to (5-24).

The amount of physics left to introduce into the program should not require a prohibitive amount of effort and should also not increase the computation time significantly. Thus, we have an interesting computer model which — with perhaps another year's effort — could become excellent. Just as the cigarette model requires further work, so does the substrate model. Perhaps the most significant improvement which still needs to be made in the latter is the introduction of a second layer.

Another important consideration is that this cigarette program could have some important non-cigarette applications — to wit, in studying smoldering in other materials and configurations. Thus, one could rewrite the code in Cartesian coordinates with relatively little effort, and examine the smoldering of a non-inert substrate in a variety of configurations.

To the extent that CIG25 is inadequate, the semi-quantitative approach used earlier can serve as an interim solution.

Finally, as to the approaches used in modeling the cigarette: it is not clear that the best numerical method for solving the equations have been used; for example, quasilinearization of the equations might make the problem more tractable.

Another item which became clear during the analysis is that the $H_2O$ produced during combustion might have an important effect that has not been at all considered, in writing down the equations: it may condense on the inner portions of the cigarette and/or on the paper wrapper, changing the characteristics of the paper. By the same token, the free water in the tobacco would also be important.

Similarly, the substrate may (a) absorb water from the cigarette, and (b) not be inert. Both of these make the substrate-heating calculation less reliable than it could be. The substrate-heating calculation can nevertheless be useful in a *relative* sense: if the calculated temperatures (which are too high) indicate that the surface temperatures do not quite reach $T_{ig}$, then it is certain that ignition will not take place.

Another "lesson" is the importance of choosing appropriate initial conditions: the first set of initial conditions was perfectly reasonable, but it takes 60 sec or longer of smoldering for the "cigarette" to relax to some approximation of a steady state; the present model numerics made that attempt impractical. Using, instead, an approximation to an experimental steady-state-distribution of oxygen and temperature permitted the program to run much more smoothly, and to relax to *its* steady state.

Aside from the numerical difficulties, the sheer magnitude of the calculation is impressive: An 18-sec "burn" on a 3-cm "cigarette" required 21 hours of calculation on a Perkin-Elmer 3252 "mini" computer. On a Cyber 855 the same calculation took about 4000 CPU seconds; a 30-sec "burn" took 7000 CPU sec, and a more "difficult" parameter set required 18000 CPU sec for a 60-sec burn. A vectorized version of the program should run quite a bit faster on a Cyber 205.

A final observation regarding the cigarette models: the basic output required of the cigarette model(s) for *this* study, is the heating flux to the substrate. The best model available heretofore (that of Muramatsu) fails in that respect, within a scale factor. The present computer model (CIG25) has the same weakness (with a different scale factor). The model will have to be completed and improved, before it is thoroughly reliable. CIG25 can be used reliably for *comparison* calculations, however; that is, if the relevant parameters are available for a given cigarette, the changes in its output flux resulting from varying one or more of its characteristics can readily be found. If the flux emitted by the original cigarette is known, therefore, the flux emitted by the altered cigarette can be predicted.

A simple alternative is to use the semi-quantitative model, which uses Muramatsu's model results, together with the correlation described by Eqs. (5-48) or (5-49). This procedure is simple and quick.

# References for Section 5


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# Appendix 5A. A Description of the Substrate Program

Program TEMPSUB has been written in ANSI '77 FORTRAN, and is therefore machine-independent, in that sense. However, it has been DIMENSIONEd so that it requires at least 132,000 words of memory. Thus, it will run (for example) on a CYBER 855. However, CDC machines have a 60-bit word, and there are no truncation-error problems. That should still be the case on a 36-bit machine. But for machines with a 32-bit word, double precision might be required.

TEMPSUB consists of a main routine and a set of subroutines. The main routine provides an interface between the user and the numerical computations performed by the subroutines FLUXFT, CTRLBC, and CENTDIFF. FLUXFT calculates the impinging flux (according to Eq. (5-5)) for each grid point on the heated surface of the substrate. A correction for the emissivity of the substrate is also made. CTRLBC calculates the surface temperature using a central difference approximation for the boundary condition (Eqs. (5-2) and (5-3)). Finally, CENTDIFF uses a central difference approximation to Eq. (5-1) to find the temperatures at all grid points within the substrate volume for as many time steps as desired. Other subroutines calculate the global energy balance for the substrate (Eqs. (5-4)).

When TEMPSUB is run, the user is presented with a menu as shown below. The values shown are default values; all values are in the MKS system, and the user can change any of the numbered items. A detailed explanation follows.

### LIST OF PARAMETERS

#### Numbered Parameters Can Be Changed

1. x/y substrate length/width ratio, 1 or 1.5
   y substrate width in meters = .2
   z substrate depth in meters = .1

2. # of meshes in y direction = 10 (25 = maximum)
   ambient temperature = 293 degrees kelvin

3. alpha (k/rho*c) = 1 E-7 M**2/sec

4. thermal conductivity = .1 watts/(m*degree kelvin)

5. H(convective) = 10 watts/(m**2*degree kelvin)
6. EMS(surface emissivity) = 0.9
7. peak flux = 10000 watts/m**2
8. X velocity = .0 m/sec
9. sigma x = .04 m
10. sigma y = .04 m
11. size ratio = 1.
12. x-sub-zero = x/2 m

Enter # for parameter change, or 0 for no more changes
?

When the question mark (?) prompt appears, the user chooses a single parameter to change by entering the appropriate item number. The program responds with a request to the user to enter the desired value. After entry of the number, the program prompts again for further changes; entering 0 halts further parameter changes for this run.

(1) allows a choice of the square or rectangular top surface. (The aspect ratio of the latter is 3:2). Note that y = 20 cm, z = 10 cm, are set here; they can be changed *via* item (11), below.

(2) sets the number of meshes in the y direction (perpendicular to the axis of the cigarette). For an x/y ratio = 1, the maximum number of meshes is 25; for an x/y ratio = 1.5 the maximum number of meshes is 18. The limit of the number of meshes is imposed by the current memory limit on the Cyber 855, (approximately 130,000 words per program).

Items (3) through (10) are self-explanatory.

(11) sets the size for the x, y, and z dimensions of the substrate. Thus a ratio of 0.5 resets all three dimensions to half the value chosen in item (1).

(12) sets the x starting position at time t = 0, assuming the end of the substrate is at x = 0.

After the parameter entries have been completed, the mesh width ($\Delta x = \Delta y = \Delta z$) and $\Delta t$(max) are calculated internally *via* Eq. (5-6), and the user is prompted to enter $\Delta t$, ($\Delta t \leq \Delta t$(max) for numerical stability).[7] Further prompts ask

[7] *Although taking $\Delta t = \Delta t(max)$ guarantees stable convergence, it does not guarantee accuracy. For numerically accurate results, one should choose $\Delta t = \Delta t(max)/10$.*

for the total number of time steps (of size $\Delta t$) and the number of steps until temperature data is to be sent to the screen and to a permanent file. When the prescribed number of time steps have elapsed, the program returns control to the user for further changes in parameters.

TEMPSUB can be run either interactively or in batch mode. For a batch run a SUBMIT file must be prepared which duplicates the user replies in interactive mode. This is a system-dependent procedure, and hence it will not be described here. The following is a listing of program TEMPSUB.

```
      PROGRAM TEMPSUB(SUBSEC,TAPE6=SUBSEC,TS,TAPE7=TS,PTEM,TAPE8=PTEM)
C     THIS PROGRAM CALCULATES THE TEMPERATURES AT GRID POINTS IN A
C     SUBSTRATE WITH AN IMPINGING FLUX ON THE (HEATED) SURFACE.  THE
C     FLUX IS SPECIFIED IN A FUNCTIONAL FORM AND CALCULATED IN SUBR.
C     FLUXFT.  SUBR. CTRLBC CALCULATES THE BOUNDARY CONDITION SURFACE
C     TEMPERATURE.  SUBR. CENTDIFF USES AN EXPLICIT CENTRAL DIFFERENCE
C     APPROXIMATION TO FIND TEMPERATURES AT ALL OF THE INTERIOR GRID
C     POINTS.  SUBR. HMAT SETS VALUES FOR THE CONVECTIVE LOSS
C     COEFFICIENT MATRIX FOR THE HEATED SURFACE (X-Y PLANE).  CURRENTLY
C     THERE ARE TWO VALUES, HUNDR (H UNDER THE CIGARETTE), AND
C     H (H ELSEWHERE).  GLOBAL ENERGY BALANCE IS CALCULATED BY SUBRS.
C     CNLOSS, EMLOSS, AND HEAT.  HEAT TRANSFERS AT SURFACES OTHER THAN
C     THE HEATED SURFACE ARE NOT INCLUDED IN THE GLOBAL ENERGY
C     CALCULATION.
C     CROSS SECTIONS STORED IN SUBSEC
C     T(I,2,1) VS. TIME STORED IN TS
C     BINARY NAME BTEMP
C     USE WITH SUBCIG SUBMIT FILE
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
      CHARACTER ASTR*60
      ASTR='*********************************************'
C     DEFAULT VALUES
C     XL=X SUBSTRATE SIZE IN M.
C     YL=Y SUBSTRATE SIZE IN M.
C     ZL=Z SUBSTRATE SIZE IN M.
C     R=SUBSTRATE SIZE RATIO:DEFAULT = 1
      XL=.3
      YL=.1
      ZL=.1
      R=1.0
C     XZRO = INITIAL X POSITION FOR FLUX PEAK
      XZRO=.15
C     XLR=X/Y SUBSTRATE LENGTH/WIDTH RATIO
      XLR=1.5
C     NMESHY = # OF MESHES IN Y DIRECTION, MAX=25
      NMESHY=10
C     STAB=STABILITY FACTOR
C     MAXIMUM TIME STEP IS  CALCULATED AS 1/2 OF COURANT CRITERION
C     IN ORDER TO ENSURE A STABLE SOLUTION.  FOR ACCURACY IN THE
C     FINITE DIFFERENCE CALCULATION THE CHOSE TIME STEP (DT)
C     SHOULD BE LESS THAN 1/5 OF THE MAXIMUM TIME STEP.
      STAB=1/12.
C     ALPHA = K/(RHO*C)
      ALPHA=1.E-7
C     THERMAL COND., EMISSIVITY,CONVECTION
      TC=.100
      EMS=0.9
      H=10.0
C     LENGTH AND WIDTH OF CIGARETTE
C     HOT END FALLS ON XZRO
      CIGLEN=.04
      CIGWID=.00334
C     H FACTOR UNDER CIGARETTE
      HUNDR=10
C     FMAX=PEAK FLUX
      FMAX=10000
C     VX=VELOCITY OF FLUX IN X DIRECTION
      VX=0
C     SIGX=FLUX WIDTH IN X DIRECTION
      SIGX=.006
C     SIGY=FLUX WIDTH IN Y DIRECTION
      SIGY=.03
C     ***********************************************************
C     START INTERACTIVE SCREEN PRINT BLOCK
C     ********************************************************
      PRINT*,'LIST OF PARAMETERS, NUMBERED PARAMETERS CAN BE CHANGED'
      PRINT'(A)',ASTR
      PRINT*,'1  X/Y SUBSTRATE LENGTH/WIDTH RATIO, 1 OR 1.5'
      PRINT*,'   Y SUBSTRATE WIDTH IN METERS = .2'
      PRINT*,'   Z SUBSTRATE DEPTH IN METERS = .1'
      PRINT*,'2  # OF MESHES IN Y DIRECTION = 10 (25 = MAXIMUM)'
      PRINT*,'   AMBIENT TEMPERATURE = 293 DEGREES KELVIN'
      PRINT*,'3  ALPHA(K/RHO*C) = 1.0E-7 M**2/SEC'
      PRINT*,'4  THERMAL CONDUCTIVITY = .1 WATTS/(M*DEGREE KELVIN)'
      PRINT*,'5  H(CONVECTIVE) = 10 WATTS/(M**2*DEGREE KELVIN)'
      PRINT*,'6  EMS(SURFACE EMISSIVITY) = .9'
      PRINT*,'7  PEAK FLUX = 10000 WATTS/M**2'
      PRINT*,'8  X VELOCITY IS 0.0 M/SEC'
      PRINT*,'9  SIGMA X IS .04 M'
      PRINT*,'10  SIGMA Y IS .04 M'
      PRINT*,'11  SIZE RATIO = 1.'
      PRINT*,'12  X-SUB-ZERO = X/2 M'
      PRINT*,'13  H(LOSS UNDER CIGARETTE) = 10 WATTS/(M**2*DEG-K.)'
      PRINT'(A)',ASTR
50    PRINT*,'ENTER # FOR PARAMETER CHANGE OR 0 FOR NO MORE CHANGES'
      READ*,IP
      IF(IP.EQ.1)THEN
      PRINT*,'ENTER LENGTH/WIDTH RATIO, 1 OR 1.5'
           READ*,XLR
           IF(XLR.LT.1.2)THEN
                XL=XL/1.5
                XZRO=XL/2
           END IF
      ELSE IF(IP.EQ.2)THEN
           PRINT*,'ENTER # OF MESHES IN Y DIRECTION, <=25'
           READ*,NMESHY
      ELSE IF(IP.EQ.3)THEN
           PRINT*,'ENTER VALUE FOR ALPHA'
           READ*,ALPHA
      ELSE IF(IP.EQ.4)THEN
           PRINT*,'ENTER VALUE FOR THERMAL CONDUCTIVITY'
           READ*,TC
      ELSE IF(IP.EQ.5) THEN
           PRINT*,'ENTER VALUE FOR CONVECTION COEFFICIENT'
           READ*,H
           HUNDR=H
      ELSE IF(IP.EQ.6) THEN
           PRINT*,'ENTER VALUE FOR EMISSIVITY'
           READ*,EMS
      ELSE IF(IP.EQ.7)THEN
           PRINT*,'ENTER VALUE FOR MAXIMUM FLUX'
           READ*,FMAX
      ELSE IF(IP.EQ.8)THEN
           PRINT*,'ENTER VALUE FOR X VELOCITY'
           READ*,VX
      ELSE IF(IP.EQ.9)THEN
           PRINT*,'ENTER VALUE FOR SIGMA X'
           READ*,SIGX
      ELSE IF(IP.EQ.10)THEN
           PRINT*,'ENTER VALUE FOR SIGMA Y'
           READ*,SIGY
      ELSE IF(IP.EQ.11)THEN
           PRINT*,'ENTER VALUE FOR SIZE RATIO'
           READ*,R
           XL=XL*R
           YL=YL*R
           ZL=ZL*R
           XZRO=XZRO*R
      ELSE IF(IP.EQ.12)THEN
           PRINT*,'ENTER VALUE FOR X ZERO'
           READ*,XZRO
      ELSE IF(IP.EQ.13)THEN
           PRINT*,'ENTER VALUE FOR H LOSS UNDER CIGARETTE'
           READ*,HUNDR
      ELSE IF(IP.EQ.0)THEN
           GO TO 60
      END IF
      GO TO 50
C     T,WT,FLUX MATRIX DIMENSIONS = GRID POINTS
C     ONE EXTRA FOR Y FOR IMAGE PLANE
60    NY=NMESHY+2
      NZ=NMESHY+1
      NX=NMESHY*3+1
      IF(XLR.LT.1.2)NX=NMESHY*2+1
C     AMBT=AMBIENT TEMPERATURE
      AMBT=293
C     SET T AND WT = 293
      DO 20 I=1,NX
      DO 20 J=1,NY
      DO 20 K=1,NZ
      T(I,J,K)=AMBT
      WT(I,J,K)=AMBT
20    CONTINUE
C     DELTA=MESH WIDTH
      DELTA=YL/NMESHY
      DTMAX=(STAB*DELTA**2)/ALPHA
      PRINT*,'MAX TIME STEP = ',DTMAX
      PRINT*,'ENTER VALUE FOR DT'
      READ*,DT
      PRINT*,'ENTER # OF TIME STEPS'
      READ*,NDT
      PRINT*,'ENTER # OF STEPS BEFORE PRINT'
      READ*,NSTEP
C     ***********************************************************
C     END INTERACTIVE SCREEN PRINT BLOCK
C     ************************************************************
      NLOOP=1
      CONVECT=0
      EMISSV=0
      DQ=0
C     CALCULATE THE BOUNDARIES OF THE INSULATED AREA UNDER
C     THE CIGARETTE
C     REAL POSITIONS
      CXLO=XZRO-.001
      CXHI=XZRO+CIGLEN+.001
      CYHI=CIGWID
      CALL HMAT(CXLO,CXHI,CYHI,HUNDR,H,DELTA,NX,NY)
      DO 500 ITIME=1,NDT
      TIME=DT*ITIME
      PTIME=DT*(ITIME-1)
      XCTR=XZRO+VX*PTIME
      CALL FLUXFT(NX,NY,DELTA,FMAX,VX,SIGX,SIGY,XZRO,TIME,DQDT,EMS)
C     SUM THE INTEGRATED FLUX
           DQ1=DQDT*DT
           DQ=DQ+DQ1
      CALL CTRLBC(ALPHA,DT,DELTA,TC,EMS,NX,NY,NZ,AMBT)
```

```
      CALL CENTDIF(ALPHA,DT,DELTA,NZ,NY,NX)
      CALL CNLOSS(AMBT,NX,NY,DELTA,CONV,DT)
C     SUM THE CONVECTIVE LOSSES FOR EACH STEP
      CONVECT=CONVECT+CONV
      CALL EMLOSS(EMS,AMBT,NX,NY,DELTA,EMLS,DT)
C     SUM THE EMISSIVE LOSSES FOR EACH STEP
      EMISSV=EMISSV+EMLS
C*****************************************************
C     FILE WRITE BLOCK
C*****************************************************
      IF(NLOOP.GE.NSTEP.OR.ITIME.GE.NDT)THEN
           CALL HEAT(TC,ALPHA,DELTA,NX,NY,NZ,TIME,HTOT,AMBT)
           WRITE(6,200)
200        FORMAT(1X,//'X LENGTH',2X,'Y MESHES',3X,'ALPHA',4X,'K',
     *7X,'H',5X,'EMS',7X,'DT',5X,'TIME',4X,'DELTA')
           WRITE(6,205)XL,NMESHY,ALPHA,TC,H,EMS,DT,TIME,DELTA
205        FORMAT(2X,F6.4,3X,I4,2X,E10.3,1X,F5.3,2X,F6.2,
     *F6.3,3X,F8.3,F8.3,F8.5)
           WRITE(6,210)
210        FORMAT(1X,//4X,'FMAX',7X,'VX',5X,'SIGX',4X,'SIGY',
     *4X,'XZRO',4X,'SIZE RATIO',3X,'EMS LOSS(J.)')
           WRITE(6,215)FMAX,VX,SIGX,SIGY,XZRO,R,EMISSV
215        FORMAT(1X,F8.1,E10.3,F8.5,F8.5,F8.5,3X,F8.5,6X,F7.2)
           WRITE(6,225)
225        FORMAT(1X,//'# OF STEPS',2X,'SUBSTRATE HEAT, JOULES',2X,
     *'INTEG. FLUX, JOULES',2X,'CONVECT LOSS, JOULES')
           WRITE(6,230)ITIME,HTOT,DQ,CONVECT
230        FORMAT(3X,I5,12X,F7.2,15X,F7.2,10X,F7.2)
           WRITE(6,112)
112        FORMAT(1X,//'SURFACE TEMPERATURE, (X-Y PLANE), LEFT HALF')
           N1=NY/2
           DO 62 II=1,NX
           WRITE(6,100)((T(II,J,1)-AMBT),J=2,N1)
62         CONTINUE
           WRITE(6,220)
220        FORMAT(1X,/'SURFACE TEMPERATURE, (X-Y PLANE), RIGHT HALF')
           DO 64 II=1,NX
           WRITE(6,100)((T(II,J,1)-AMBT),J=N1+1,NY)
64         CONTINUE
           IC=XCTR/DELTA+1.5
           WRITE(6,114)
114        FORMAT(1X,//'CROSS-SECTION AT PEAK IN X, (Y-Z PLANE)')
      DO 70 K=1,NZ
           WRITE(6,100)((T(IC,J,K)-AMBT),J=2,N1)
70         CONTINUE
           WRITE(6,116)
116        FORMAT(1X,//'LONGITUDINAL SECTION, Y=0, (X-Z PLANE)')
           N2=NZ/2
           DO 72 II=1,NX
           WRITE(6,100)((T(II,2,K)-AMBT),K=1,N2)
72         CONTINUE
           WRITE(6,118)
118        FORMAT(1X,//'FLUX ON SURFACE, (X-Y PLANE)')
           DO 74 II=1,NX
           WRITE(6,100)(FLUX(II,J),J=2,N1)
74         CONTINUE
           WRITE(6,120)
120        FORMAT(1X,//'CONVECTIVE MATRIX, (X-Y PLANE)')
           DO 300 II=1,NX
           WRITE(6,310)(HM(II,J),J=2,NY)
310        FORMAT(1X,25(F3.0,2X))
300        CONTINUE
      END IF
100   FORMAT(1X,15(F8.2,1X))
C*****************************************************
C     PLOT FILE WRITE BLOCK
C*****************************************************
      IF(NLOOP.GE.NSTEP.OR.ITIME.GE.NDT)THEN
           NHORZ=NX
           NVERT=NY-1
           WRITE(8,*)NHORZ,NVERT,TIME,DELTA
C          SURFACE TEMPERATURE
           DO 800 I5=2,NY
           WRITE(8,600)((T(I6,I5,1)-AMBT),I6=1,NX)
800        CONTINUE
600        FORMAT(20F6.0)
      END IF
C*****************************************************
C     SCREEN PRINT BLOCK
C*****************************************************
      IF(NLOOP.GE.NSTEP.OR.ITIME.GE.NDT)THEN
           TIME=DT*ITIME
           I2=(NX-1)/2+6
           I1=I2-10
           CALL SFLUX(I1,I2,2,6,DQDT,ITIME,TIME)
           CALL STEMP(I1,I2,2,6,ITIME,TIME)
           CALL CSECT(XCTR,2,6,1,10,ITIME,DELTA,TIME)
           CALL HEAT(TC,ALPHA,DELTA,NX,NY,NZ,TIME,HTOT,AMBT)
           PRINT*,'CONVECTIVE LOSS = ',CONVECT
           NLOOP=1
           IF(ITIME.LT.NDT)THEN
                PRINT*,'ENTER # OF STEPS BEFORE PRINT'
                READ*,NSTEP
           END IF
      ELSE
           NLOOP=NLOOP+1
      END IF
*C    MAKE A FILE OF T(I,2,1) FOR EACH TIME STEP
      IF(ITIME.EQ.1)THEN
           NDD=NDT/5
           WRITE(7,*)NX,NY,NZ,DELTA,R,VX,DT,XZRO,NDD,ALPHA,H,TC,SIGX
      END IF
      IF(MOD(ITIME,5).EQ.0)THEN
      PTIME=ITIME*DT
      WRITE(7,*)PTIME
      WRITE(7,490)( (T(I,2,1)-AMBT),I=1,NX)
490   FORMAT(15F7.1)
      END IF
500   CONTINUE
      PRINT*,'DO ANOTHER CALC?  1 = YES'
      READ*,NNN
      IF(NNN.EQ.1) GO TO 50
      STOP
      END
C     ****************************************************
      SUBROUTINE SFLUX(I1,I2,J1,J2,DQDT,ITIME,TIME)
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
      PRINT*,'FLUX DISTRIBUTION'
      PRINT*,'STEP =  ',ITIME,'  TIME =  ',TIME,'  DQDT=  ',DQDT
      DO 50 I=I1,I2
      PRINT 10,(FLUX(I,J),J=J1,J2)
50    CONTINUE
10    FORMAT(1X,8(F8.2,1X))
      RETURN
      END
      SUBROUTINE STEMP(I1,I2,J1,J2,ITIME,TIME)
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
      PRINT*,'SURFACE TEMPERATURE'
      PRINT*,'STEP =  ',ITIME,'  TIME =  ',TIME
      DO 50 I=I1,I2
      PRINT 10,(T(I,J,1),J=J1,J2)
50    CONTINUE
10    FORMAT(1X,8(F8.2,1X))
      RETURN
      END
      SUBROUTINE CSECT(XCTR,J1,J2,K1,K2,ITIME,DELTA,TIME)
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
      PRINT*,'CROSS SECTION AT XCTR'
      PRINT*,'STEP =  ',ITIME,'  TIME =  ',TIME,'  XCTR =  ',XCTR
C     TEMPORARY FIX FOR XCTR(REAL)
      I=XCTR/DELTA+1.5
      DO 50 K=K1,K2
      PRINT 10,(T(I,J,K),J=J1,J2)
50    CONTINUE
10    FORMAT(1X,8(F8.2,1X))
      RETURN
      END
C     *******************************************************
      SUBROUTINE CENTDIF(ALPHA,DT,DELTA,NZ,NY,NX)
C     SUBROUTINE FOR CENTRAL DIFFERENCE CALCULATION
C     ALPHA=K/(RHO*C),DT=TIME STEP,DELTA=MESH SIZE IN METERS
C     ENTER WITH BC'S IN K=1 PLANE OF T MATRIX
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
C     FILL IMAGE PLANE (J=1) WITH J=3 VALUES
      DO 50 I=2,NX
      DO 50 K=2,NZ
      T(I,1,K)=T(I,3,K)
50    CONTINUE
C     SET CONSTANTS
      C1=ALPHA*DT/(DELTA**2)
      C2=1-6*C1
C     CALCULATE NEW VALUES OF TEMPERATURE
      DO 100 K=2,NZ-1
      DO 100 J=2,NY-1
      DO 100 I=2,NX-1
      AVG6=T(I+1,J,K)+T(I-1,J,K)+T(I,J+1,K)+T(I,J-1,K)+
     *T(I,J,K+1)+T(I,J,K-1)
      WT(I,J,K)=C2*T(I,J,K)+C1*AVG6
100   CONTINUE
C     PUT WT IN T FOR NEXT ITERATION
      DO 200 K=2,NZ-1
      DO 200 J=2,NY-1
      DO 200 I=2,NX-1
      T(I,J,K)=WT(I,J,K)
200   CONTINUE
      RETURN
      END
C     ****************************************************
      SUBROUTINE CTRLBC(ALPHA,DT,DELTA,TC,EMS,NX,NY,NZ,AMBT)
C     SUBROUTINE FOR CENTRAL DIFFERENCE BOUNDARY CONDITIONS
C     H=CONVECTION, DELTA=MESH SIZE
C     TC=THERMAL COND., EMS=SMISSIVITY
C     EXIT WITH T(I,J,1) FILLED
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
      SBC=5.67E-8
      TAIR=AMBT
      C1=ALPHA*DT/(DELTA**2)
      C3=2*DELTA/TC
      B=-C1*EMS*SBC*C3
      C=C1*C3
      D=C1
      E=C1*C3*EMS*SBC*TAIR**4
C     FILL IMAGE PLANE
      DO 50 I=1,NX
      DO 50 K=1,NZ
      T(I,1,K)=T(I,3,K)
50    CONTINUE
      DO 200 J=2,NY-1
      DO 200 I=2,NX-1
      F=E+C1*C3*HM(I,J)*TAIR
      AA=1-6*C1-C1*C3*HM(I,J)
      AVG5=T(I+1,J,1)+T(I-1,J,1)+T(I,J+1,1)+T(I,J-1,1)
     *+2*T(I,J,2)
      WT(I,J,1)=AA*T(I,J,1)+B*T(I,J,1)**4+FLUX(I,J)*C
     *+D*AVG5+F
200   CONTINUE
C     FILL T(I,J,1) PLANE
```

```
      DO 300 J=2,NY-1
      DO 300 I=2,NX-1
      T(I,J,1)=WT(I,J,1)
300   CONTINUE
      RETURN
      END
C     **********************************************
      SUBROUTINE HEAT(TC,ALPHA,DELTA,NX,NY,NZ,TIME,HTOT,AMBT)
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
C     CALCULATE TOTAL HEAT IN JOULES FOR ENTIRE SUBSTRATE
      SUMT=0
      DO 50 I=1,NX-1
      DO 50 J=2,NY-1
      DO 50 K=1,NZ-1
      T1=T(I,J,K)+T(I+1,J,K)+T(I,J+1,K)+T(I,J,K+1)
      T2=T(I+1,J+1,K)+T(I+1,J+1,K+1)+T(I+1,J,K+1)+T(I,J+1,K+1)
      SUMT=SUMT+(T1+T2)/8.-AMBT
50    CONTINUE
      HTOT=SUMT*(TC/ALPHA)*2*DELTA**3
      PRINT*,'TOTAL HEAT IS  ',HTOT,'  TIME IS  ',TIME
      PRINT*,'SUMT=', SUMT
      RETURN
      END
C     ***********************************************
      SUBROUTINE CNLOSS(AMBT,NX,NY,DELTA,CONV,DT)
C     CALCULATE CONVECTIVE LOSS PER STEP FOR ENTIRE SURFACE
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
      CONV=0
      DO 50 I=2,NX-1
      DO 50 J=3,NY-1
      CONV=CONV+HM(I,J)*(T(I,J,1)-AMBT)
50    CONTINUE
C     TAKE CARE OF J=2  DIVIDE BY 1/2 FOR FLUX 1/2 ON GRID POINT
      DO 55 I=2,NX-1
      CONV=CONV+HM(I,J)*(T(I,2,1)-AMBT)/2.
55    CONTINUE
      CONV=CONV*DELTA**2*DT*2
      RETURN
      END
C     ****************************************************
      SUBROUTINE EMLOSS(EMS,AMBT,NX,NY,DELTA,EMLS,DT)
C     CALCULATE EMISSIVE LOSS PER STEP FOR ENTIRE SURFACE
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
      SBC=5.67E-8
      EMLS=0
      TAIR=293
      DO 50 I=2,NX-1
      DO 50 J=3,NY-1
      EMLS=EMLS+EMS*SBC*(T(I,J,1)-TAIR)**4
50    CONTINUE
C     J=2, 1/2 FLUX ON GRID POINT
      DO 55 I=2,NX-1
      EMLS=EMLS+(T(I,2,1)-TAIR)/2.
55    CONTINUE
      EMLS=EMLS*DELTA**2*DT*2
      RETURN
      END
```

```
C     ****************************************************
      SUBROUTINE FLUXFT(NX,NY,DELTA,FMAX,VX,SX,SY,XZRO,TIME,FSUM,EMS)
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
C     FIND FLUX FOR EACH I,J
C     MULTIPLY EACH FLUX BY EMS
      DO 50 I=1,NX
      DO 50 J=2,NY
C     X,Y COORDINATES OF I,J GRID POINTS
      XP=(I-1)*DELTA
      YP=(J-2)*DELTA
      X=XP-XZRO-VX*TIME
C     FUNCTION
C     WATCH FOR UNDERFLOW
      EA=(X/SX)**2
      EB=(YP/SY)**2
      IF(EA.GT.25..OR.EB.GT.25.)THEN
         FLUX(I,J)=0
      ELSE
         PA=EXP(-EA)
         PB=EXP(-EB)
         FLUX(I,J)=PA*PB*FMAX*EMS
      END IF
50    CONTINUE
C     INTEGRATED FLUX,DQ/DT, INCLUDING IMAGE 1/2 PLANE
      FSUM=0
      DO 100 I=1,NX
      DO 100 J=2,NY
C     CORRECT FOR IMAGE BOUNDARY 1/2 AREA UNDER FLUX
      IF(J.EQ.2)THEN
         FSUM=FSUM+FLUX(I,J)/2
      ELSE
         FSUM=FSUM+FLUX(I,J)
      END IF
100   CONTINUE
      FSUM=FSUM*2*DELTA**2
      RETURN
      END
C     ****************************************************
      SUBROUTINE HMAT(CXLO,CXHI,CYHI,HUNDR,H,DELTA,NX,NY)
C     CALCULATES CONVECTIVE LOSS MATRIX FOR USE
C     CTRLBC AND CNLOSS
      COMMON T(55,29,28),WT(55,29,28),FLUX(55,29),HM(55,29)
C     CALCULATE THE GRID POSITIONS, LOCK TO NEAREST GRID
      NXLO=CXLO/DELTA+1.5
      NXHI=CXHI/DELTA+1.5
      NYHI=CYHI/DELTA+2.5
C     FILL HM MATRIX WITH H AND HUNDR VALUES
      DO 50 I=1,NX
      DO 50 J=1,NY
50    HM(I,J)=H
C     NOW FILL THE RECTANGLE UNDER THE CIGARETTE WITH HUNDR
      DO 100 I=NXLO,NXHI
      DO 100 J=2,NYHI
100   HM(I,J)=HUNDR
      RETURN
      END
```

# Appendix 5B.
## The Cigarette Program CIG25

This appendix contains a brief description of the cigarette code CIG25 and describes the procedure required to operate the code on the CYBER 855 computer. This program, too, is in standard FORTRAN. A version of CIG25 will also operate on the CYBER 205 and on the Perkin Elmer 3252 minicomputer. The physics contained in CIG25 includes thermal diffusion with a temperature-dependent diffusion coefficient, oxygen diffusion with a temperature-dependent diffusion coefficient, gas flow in the radial direction, combustion with a one-step Arrhenius equation, convective thermal boundary conditions, and oxygen porosity at the boundary which includes the effects of paper. The resulting nonlinear partial differential equations are solved using the implicit Crank-Nicolson method with a Gauss-Seidel over-relaxation solver.

The program structure consists of a main program with twelve subroutines and two function routines. The main program handles the input of program variables, calling of the subroutines to calculate the physics, testing for convergence after each iteration loop, and calling of the output subroutines.

Subroutines TEMP and OXY calculate the heat and oxygen diffusion, respectively; subroutine VELOCR calculates the radial velocity of the gas flow, and subroutine REACT calculates the reaction rate of the combustion occurring in the cigarette.

The initial data file for temperature, oxygen fraction, density fraction, and velocity is generated by subroutine INITIAL, or read from an external data file by subroutine INITD. The results of the calculations are output to an external file by the subroutines OUTPUT and OUTPUTP.

The other four subroutines in the code: TEST, TESTT, TRAPE, and OTRAPE, were used to test the diffusion calculations and calculate energy and oxygen conservation for earlier versions of the code. The present code has been changed sufficiently that these subroutines will need some coding changes before they will work with the additional physics now included. They must therefore be bypassed, which is accomplished with the indicated answers to questions 1 and 2 of the input, as will be shown below.

The procedure detailed below enables a user to operate the cigarette program CIG25 on the Cyber 855. When run, the program will output the results of the calculation to file TEM25. This output file may then be listed out to a printer or plotted by a laser printer using the graphics code PLOTT25.

There are several options available to the user when CIG25 is submitted to the computer. While the code can be operated interactively, usually a batch submission is more desirable since the CPU time required to complete a job can exceed one hour on a Cyber 855. The user has an option to use an internally generated initial input file to define the initial temperature, oxygen fraction, density fraction, and radial flow velocity, or to input an external set of values using the data file ITEM1. The first option corresponds to the "initial" condition, meant to simulate the result of using a match to light the cigarette, and shown in Figure 5-14a. At present, ITEM1 contains an initial condition corresponding to the data on temperature and oxygen fraction from an experiment by Baker (see Ref. [5-1]). An assumed density fraction distribution is used along with a zero initial velocity distribution.

A second user option is to select either an input mode where most of the constant variables are input using the keyboard or to use an input mode where the variables are submitted in a batch file. A variation on this mode of input is a second mode where only those variables which are likely to change are input externally, with the other variables being initialized within the program. Examples of both input modes are given below.

To run the cigarette code interactively, the compiled code must be attached to the users' job using the command "GET,BCIG25A". To run the code, the command "BCIG25A" is entered on the terminal. The following list of prompts will appear with either suggested or required responses.

| PROMPT | ANSWER |
|---|---|
| Enter 1 to test gasdiff routines | 2 (required) |
| Enter 1 to test temp diff routines | 2 (required) |
| Enter 1 if standard input values<br>Enter 2 if changed input values | 2 if you only wish to change a limited set of variables,<br>3 if you wish to change most of the variables. |

If choice 3 is selected, a series of prompts for virtually all the variables used in the program will appear with a request for input values. If choice 2 is selected, a limited number of prompts will appear with a request for input. Generally, most of the prompts will be self-explanatory. The few that need some explanation are:

| PROMPT | ANSWER |
|---|---|
| Enter number of grids in R. | 20 (for consistency: the first value of the DIMENSION and PARAMETER statements equals no. of grids + 1 and is currently 21). |
| Enter number of timesteps for energy balance check. | This routine has not yet been updated, therefore enter a number larger than the desired number of timesteps. |
| Enter length ratio Z to R | 7.5 (This input determines the length of the "cigarette," relative to its radius. The second value in the DIMENSION and PARAMETER statements must equal NG*RATIO+1, and is currently 151). |

An example of a batch SUBMIT file, SUB25A, is given below. The SUBMIT file is specific to the CYBER, but the equivalent control file for some other machine or operating system should be readily prepared by your system operator. The SUBMIT file supplies the operating set of parameters for the machine, such as the operating class, the maximum (CPU) time the program should run, the user ID and password, the name of the program to be run, the names of the data files to be used, and the name(s) of the output file(s). Then the "data stream," consisting of the answers to the prompts (questions) which would appear on the screen if the program were being run interactively, is given. Some of those prompts are shown above, but the list was not complete. We now list the complete set of prompts, followed by a batch SUBMIT file (SUB25A). The input parameters given in SUB25A after the end-of-record mark correspond to the following prompts:

Enter 1 to test gasdiff. routines.
Enter 1 to test temp diff routine.
Enter 1 if standard input values are desired.
Enter 2 if improved input values are desired.
Enter the number of grids in R.
Enter the number of timesteps and num timesteps data out.
Enter number of timesteps for energy balance check.
Enter the value for oxy diff coef, def. val. = 1.2.
Enter the value of GAR and GARP. default values = 5.4, 2.7.
Enter H = HR/K.
Enter B to change pre-exponential factor. Default value = 3.8 E13
Enter 1 to read an existing data file.
Enter timestep for first 50 iterations in seconds.
Enter timestep for iterations gt. 50 in seconds.
Enter err for iterations.
Enter IT and TIM
To run the SUBMIT file, type SUBMIT, SUB25A, E
An example SUBMIT file for a run is:

```
SUB25A,SCI1,T=11000.
USER,HEN,CIGAR.
GET,BCIG25A.
GET,ITEM1.
DEFINE,TEM25.
BCIG25A.
EXIT.
DEFINE,TEM25.
2
2
2
20
6000
400
8000
.70000
1.00
.500
1.50
9.25E12
1
.005
.005
.001
0
0.
```

The data used for the run shown in the text is given in Table A-1 below,
followed by the listing for CIG25.

**Table 5-B-1. Parameter Values Used for the Sample Run in the Text, Using Program CIG25**

| Physical parameter | Description | Parameter value used in program |
|---|---|---|
| $\rho_{so} = 0.74$ g/cm³ <br> $\rho_g = 1.18 \times 10^{-3}$ g/cm³ | Density of shred <br> Density of air | $D1 \equiv \rho_{so}/\rho_g = 627$ |
| $\rho_{co} = 0.252$ g/cm³ | Density of char | $D2 \equiv \rho_{co}/\rho_{so} = 0.341$ |
| $\rho_{ao} = 0.0962$ g/cm³ | Density of ash | $AN \equiv \rho_{ao}/\rho_{so} = 0.13$ |
| $n_{02} = 1.64$ | $\frac{\text{Oxygen mass}}{\text{Char mass}}$ in tobacco combustion | $CN \equiv n_{02} = 1.64$ |
| $R = 0.4$ cm | Cigarette radius | (normalizing constant) |
| $C_s = 1.043$ J/g°C | Specific heat of solid | $A \equiv (\rho_{so} C_s R^2)^{-1} = 8.1$ cm°C/J |
| $D_o = 0.112$ cm²/sec | Diffusion coefficient for oxygen in the tobacco column, at ambient temperature | $D \equiv D_o/R^2 = 0.7\ \text{sec}^{-1}$ |
| $H_c = Q_h = 4200$ cal/gm <br> $= 17570$ J/gm | Heat of combustion of char | $C \equiv \frac{Q_h}{C_s} = 16800$ K |
| $\phi = 0.65$ | Void fraction | $PH \equiv \phi = 0.65$ |
| $E_{co} = 1.7 \times 10^5$ J/g mole | Activation energy for char oxidation | $E \equiv \frac{E_{co}}{R_g}$ 20400 K ($E_{co}$ in terms of the gas constant) |
| $Z_{co} = 3.78 \times 10^{11} \frac{\text{cm}^3}{\text{g sec}}$ | Pre-exponential factor for char oxidation | $B \equiv \rho_{so} Z_{co} = 2.8 \times 10^{11}\ \text{sec}^{-1}$ |
| $\gamma_g = 0.8$ cm/sec | Mass transfer coefficient through boundary layer | $GAR \equiv \gamma_g/R = 2.0\ \text{sec}^{-1}$ |
| $\gamma_p = 0.089$ cm/sec | Mass transfer coefficient through (virgin) paper | $GARP \equiv \frac{1}{R}\left(\frac{1}{\gamma_p}+\frac{1}{\gamma_g}\right)^{-1} = 0.2\ \text{sec}^{-1}$ |
| $T_p = 450$°C | Temperature at which the paper disintegrates | $TP = 723$ K |
| $h' = 50.6 \frac{\text{W}}{\text{m}^2\text{°C}}$ | Effective heat transfer coefficient | $H \equiv \frac{h' R}{k(300)} = 1.9$ |
| $k_g = 4.514 \times 10^{-4}$ W/cm°C | Thermal conductivity of the gas | $GK \equiv k_g$ W/cm K |
| $k_s = 3.16 \times 10^{-3}$ W/cm°C | Thermal conductivity of the solid | $KF \equiv k_s$ W/cm K |
| $D_p = 0.0575$ cm | Pore diameter | $DP \equiv D_p$ |
| $\varepsilon_t = 0.98$ | Emissivity of smoldering coal | $ET \equiv \varepsilon_t$ |
| $\Phi = 0.82$ | Total void fraction | $PH1 \equiv \Phi$ |
| The last five items above are used in Eq. (5-50), for the effective thermal conductivity in the cigarette. | | |
| $\Delta t = 0.005$ sec | Size of time steps | $TS \equiv \Delta t$ |
| $\left\lvert \frac{\Delta x_{ij}}{x_{ij}} \right\rvert < \varepsilon$ | Convergence criterion | $ERR \equiv \varepsilon = 10^{-3}$ |

```
      PROGRAM CIG25(TEM25,ITEM1,TAPE6=TEM25,TAPE7=ITEM1)
      DIMENSION T(21,151),Y(21,151),R(21,151),W1(21,151),W2(21,151)
     1,GA(151),W3(21,151),RR(21,151),Y1(21,151),R1(21,151),T1(21,151)
     2,U(21,151),W4(21,151),U1(21,151),RR1(21,151),RRW(21,151)
C     PROGRAM SOLVES PDE EQUATIONS USING CRANK-NICHOLSON TECHNIQUE
C     OXYGEN PDE IS SOLVED ITERATIVELY USING GAUSS-SEIDEL TECHNIQUE
C     TEMPERATURE PDE IS SOLVED ITERATIVELY USING A GAUSS-SEIDEL
C     TECHNIQUE
C     THE VELOCITY IS CALCULATED BASED ON THE ASSUMPTION THAT THE
C     GAS DENSITY IS CONSTANT.  THE RESULTING DIFFERENTIAL EQ. IS
C     INTEGRATED USING THE TRAPEZOID RULE.
C     TWO TIME STEPS CAN BE CHOSEN. THE FIRST TIME STEP IS USED FOR
C     THE FIRST 50 TIMESTEPS AND THE SECOND TIMESTEP IS USED FOR
C     ALL SUBSEQUENT TIMESTEPS.
C     PAPER IS CONSIDERED POROUS WITH POROSITY GARP
C     PROGRAM HAS THE SAME PHYSICS AS CIG21A AND ALSO INCLUDES
C     A TEMPERATURE DEPENDENT THERMAL DIFFUSION COEFFICIENT.
C     CONVECTIVE COOLING AT THE SURFACE
      NNN=0
      PRINT*,'ENTER 1 TO TEST GASDIFF. ROUTINES'
      READ*,NNN
      IF(NNN.EQ.1) CALL TEST
      IF(NNN.EQ.1) GO TO 50
      PRINT*,'ENTER 1 TO TEST TEMP DIFF ROUTINE'
      READ*,MMM
      IF(MMM.EQ.1) CALL TESTT
      IF(MMM.EQ.1)GO TO 50
      PRINT*,'ENTER 1 IF STANDARD INPUT VALUES ARE DESIRED'
      PRINT*,'ENTER 2 IF IMPROVED INPUT VALUES ARE DESIRED.'
      READ*,NN
      IF(NN.GT.2) GO TO 5
      IF(NN.EQ.2) GO TO 2
      D=.7
      A=.028
      B=5.5E16
      C=1.68E04
      E=2.266E04
      D1=220.
      D2=.341
      PH=.65
      TP=723.
      BE=.01
      GAR=1.0
      GARP=.5
      AN=.13
      CN=1.6428
      RIZR=8
      H=.50
      SPHGS=.5
      GO TO 3
2     D=1.2
C     THE OXY DIFF COEF HAS BEEN DECREASED BY A FACTOR OF 2
C     OVER THE IMPROVED INPUT VALUE. IT IS NOW MURAMATSU VALUE.
C     NOTE THAT A=1/DS*CS*R**2 WHICH DIFFERS FROM CIG21
      A=8.0964
      B=3.7E13
      C=1.68E04
      E=2.266E04
C     D1 HAS BEEN RECALULATED FROM A VALUE OF 1220 TO PRESENT
C     BY CONSIDERING THE TOBACCO SHRED POROUS
      D1=627
      D2=.341
      PH=.65
      TP=723.
      GAR=5.4
      GARP=2.7
      AN=.13
      CN=1.6428
      RIZR=7.5
      SPHGS=.5
      H1=1.386
      DP=.0575
      GK=4.514E-4
      FK=3.16E-3
      ET=.98
      PH1=.82
3     ERR=.001
      PRINT*,'ENTER NUMBER OF GRIDS IN R'
      READ*,NG
      PRINT*,'ENTER NUMBER OF TIMESTEPS AND NUM TIMESTEPS DATA OUT'
      READ*,ISP,INP
      PRINT*,'ENTER NUMBER OF TIMESTEPS FOR ENERGY BALANCE CHECK'
      READ*,IEB
      PRINT*,'ENTER THE VALUE FOR OXY DIFF COEF, DEF. VAL.=1.2'
      READ*,D
      PRINT*,'ENTER THE VALUE OF GAR AND GARP. DEFAULT VALUES = 5.4,2.7'
      READ*,GAR,GARP
      PRINT*,'ENTER H =HR/K'
      READ*,H
      PRINT*,'ENTER B TO CHANGE PRE-EXPONENTIAL FACTOR. D.V.=3.8E13'
      READ*,B
      PRINT*,'ENTER E TO CHANGE EXPONENTIAL. D.V.=2.266E04'
      READ*,E
      PRINT*,'ENTER 1 TO READ EXISTING DATA FILE'
      READ*,IDATA
      GOTO 8
5     PRINT*,'ENTER GAS AND DEN*SPECHT/R**2, D/R**2, 1/DS*CS*R**2'
      READ*,D,A
      PRINT*,'ENTER THERMAL RELEASE RATE/GAS DEN RC/DG RC=DS*DG*ZC'
      READ*,B
      PRINT*,'ENTER HEAT/GM/SPECIFIC HEAT Q/CS AND REACTION EXP E/R'
      READ*,C,E
      PRINT*,'ENTER RATIO SOLID/GAS DEN, CHAR/SOLID DEN D1,D2'
      READ*,D1,D2
      PRINT*,'ENTER VOID FRACTION PHI=PH, IGNIT TEMP FOR PAPER TP'
      READ*,PH,TP
      PRINT*,'ENTER BETA=BE,GAMMA/R=GAR,GARP WHICH IS PAPER POROSITY'
      READ*,BE,GAR,GARP
      PRINT*,'ENTER G ASH/G TOB=AN AND G OXY/G GAS CN'
      READ*,AN,CN
      PRINT*,'ENTER MAXIMUM CHANGE FOR STEADY STATE CONDITIONS, ERR'
      READ*,ERR
      PRINT*,'ENTER NUMBER OF GRIDS IN R AND NUMBER OF TIMESTEPS ISP'
      READ*,NG,ISP
      PRINT*,'ENTER GRID RATIO Z TO R'
      READ*,RIZR
      PRINT*,'ENTER CONVECTION COEF H=HR/K, NUM TIMESTEP FOR DATA INP'
       PRINT*,'K IS THE THERMAL CONDUCTIVITY AT 300K'
      READ*, H1,INP
      PRINT*,'ENTER RATIO SPEC. HEAT OF AIR TO SPEC. HEAT OF TOB.'
      READ*,SPHGS
      PRINT*,'ENTER DIAMETER OF VOID SPACE(CM)DP, RAD. EMISSIVITY ET'
      READ*,DP,ET
      PRINT*,'ENTER THERMAL COND OF GAS GK, THERMAL COND OF SOLID FK'
      READ*,GK,FK
    8 IT=0
      TIM=0.
      ISKIP=1
      NTEST=0
      W=.9
      K1=1
      K=1
      TA=293.
      YA=.232
      A1=(1-PH1**(2./3.))*FK+GK*PH1**(1./3.)
      A2=1.5109E-11*ET*DP*PH1**(1./3.)
      IEBN=0
      A3=1.133E-11*DP*ET*PH**(1./3.)
      IN=0
      NR=NG+1
      NZ=NG*RIZR+1
      PRINT*,'ENTER TIMESTEP FOR FIRST 50 ITERATIONS IN SECONDS'
      READ*,TS1
      PRINT*,'ENTER TIMESTEP FOR ITERATIONS GT 50 IN SECONDS'
      READ*,TS2
      TS=TS1
      PRINT*,'ENTER ERR FOR ITERATIONS'
      READ*,ERR
C     INITIALIZE MATRIX
      IF(IDATA.EQ.1) THEN
      PRINT*,'ENTER IT,TIM'
      READ*,IT,TIM
      CALL INITD(T,Y,R,U,W1,W2,W3,W4,GA,GAR)
      ELSE
      CALL INITIAL(TA,T,Y,R,NR,NZ,GA,W2,W3,W4,U)
      END IF
      IF (IT.EQ.0) THEN
      WRITE(6,124)
124   FORMAT('INITIAL CONDITIONS')
      CALL OUTPUTP(D,A,B,C,E,D1,D2,PH,TP,GAR,GARP,AN,CN,H,NG,
     1RIZR,IN,TS,TIM)
      CALL OUTPUT(NR,NZ,T,Y,R,U)
      END IF
C     CALCULATE REACTION RATE FROM DIFFERENTIAL EQ
10    CALL REACT(T,R,NR,NZ,W1,B,D1,Y,TS,E,W2,W3,RR,K1,RRW)
C     CALCULATE OXYGEN DIFFUSION
      CALL OXY(NG,D,TS,PH,B,AN,E,D2,CN,Y,T,R,GAR,W2,
     1NR,NZ,GA,TP,YA,RR,D1,U,W4,RRW,W3,TA,ISKIP,GARP,W)
C     CALCULATE TEMPERATURE
      CALL TEMP(NG,A,B,C,D1,D2,NR,NZ,PH,TS,E,T,H1,TA,R,Y,RR,W3,
     1U,W4,SPHGS,RRW,ISKIP,W,A1,A2,A3)
C     CALCULATE VELOCITY/R0
      CALL VELOCR(PH,AN,D1,D2,NG,NR,NZ,RR,W4,U,RRW)
C     TEST FOR CONVERGENCE
      RESID=0.
      DEL=0.
      DO 40 I=1,NR
      DO 30 J=1,NZ
      IF(K1.EQ.1) THEN
      RR1(I,J)=RR(I,J)
      Y1(I,J)=W2(I,J)
      R1(I,J)=W1(I,J)
      T1(I,J)=W3(I,J)
      U1(I,J)=W4(I,J)
      ELSE
      IF(W2(I,J).GT.0.) THEN
      RESID=ABS((Y1(I,J)-W2(I,J))/W2(I,J))
      ELSE IF(Y1(I,J).GT.0.) THEN
      RESID=ABS((Y1(I,J)-W2(I,J))/Y1(I,J))
      END IF
      IF(RESID-DEL.GT.0.) DEL=RESID
      RESID=ABS((T1(I,J)-W3(I,J))/T1(I,J))
      IF(RESID-DEL.GT.0.) DEL=RESID
      IF(U1(I,J).GT.0.) THEN
      RESID=ABS((U1(I,J)-W4(I,J))/U1(I,J))
      ELSE IF(W4(I,J).GT.0.) THEN
      RESID=ABS((U1(I,J)-W4(I,J))/W4(I,J))
      END IF
      IF(RESID-DEL.GT.0.) DEL=RESID
C     IF(RR1(I,J).GT.0.) THEN
C     RESID=ABS((RR1(I,J)-RRW(I,J))/RR1(I,J))
C     ELSE IF(RR(I,J).GT.0.) THEN
C     RESID=ABS((RR1(I,J)-RRW(I,J))/RRW(I,J))
C     END IF
C     IF(RESID-DEL.GT.0.)DEL=RESID
      Y1(I,J)=W2(I,J)
      R1(I,J)=W1(I,J)
      U1(I,J)=W4(I,J)
      RR1(I,J)=RRW(I,J)
      T1(I,J)=W3(I,J)
      END IF
30    CONTINUE
40    CONTINUE
      IF(K1.EQ.1) THEN
      K1=2
      DEL=1.
      END IF
      IF(K.GT.300) GO TO 400
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      K=K+1
      ISKIP=2
      IF(DEL.GT.ERR) GO TO 10
      IT=IT+1
      IEBN=IEBN+1
      IF(IEBN.EQ.IEB) THEN
C     TEST FOR ENERGY AND OXYGEN BALANCE
      IEBN=0
      CALL TRAPE(I,J,T,W3,NR,NZ,TS,PH,A,H,R,Y,E,TA,B,C,D1,D2)
      CALL OTRAPE(I,J,T,W3,NR,NZ,TS,PH,CN,GAR,R,Y,E,TA,B,C,GA,W2)
      END IF
C     UPDATE VARIABLES FOR NEXT TIMESTEP
      DO 80 I=1,NR
      DO 75 J=1,NZ
      R(I,J)=W1(I,J)
      Y(I,J)=W2(I,J)
      T(I,J)=W3(I,J)
      U(I,J)=W4(I,J)
75    CONTINUE
80    CONTINUE
      ISKIP=1
      IN=IN+1
      IF(IT.EQ.50) TS=TS2
C     INTERMEDIATE OUTPUT
      IF(IN.EQ.INP) THEN
      IF(IT.GE.50) THEN
      TIM=50*TS1+(IT-50)*TS2
      ELSE
      TIM=IT*TS1
      END IF
      IF(IN.EQ.INP) IN=0
      WRITE(6,102) TS,TIM
102   FORMAT('TIME STEP =',E9.3,'TIME =',E9.3)
      CALL OUTPUT(NR,NZ,T,Y,R,U)
      VALT=0.
      DO 90 I=1,NR
      DO 85 J=1,NZ
      IF(T(I,J).GT.VALT) VALT=T(I,J)
85    CONTINUE
90    CONTINUE
      IF(VALT.GE.1500.) THEN
      PRINT*,'TEMP EXCEEDS 1500 K'
      STOP
      ELSE IF(VALT.LT.700.) THEN
      PRINT*,'MAXIMUM TEMP BELOW 700.K'
      STOP
      END IF
      END IF
C     FINAL OUTPUT
      IF(IT.GE.ISP) THEN
      PRINT*,'PROGRAM REACHED LAST TIME STEP!!'
      IF(IT.GE.50) THEN
      TIM=50*TS1+(IT-50)*TS2
      ELSE
      TIM=IT*TS1
      END IF
      WRITE(6,108)
108   FORMAT('CIG25A OUTPUT')
      CALL OUTPUT(NR,NZ,T,Y,R,U)
      STOP
      END IF
      K=1
      K1=1
      GO TO 10
400   PRINT*,'FAILED TO CONVERGE IN GLOBAL SCHEME'
      WRITE(6,109) IT,DEL
      CALL OUTPUT(NR,NZ,T,Y,R,U)
109   FORMAT('TIMESTEP WHICH CIG25A DIDNT CONVERGE',I5,'DEL= ',F7.3)
      STOP
50    CONTINUE
      END
      SUBROUTINE INITD(T,Y,R,U,W1,W2,W3,W4,GA,GAR)
      PARAMETER(NR=21,NZ=151)
      DIMENSION T(NR,NZ),Y(NR,NZ),R(NR,NZ),U(NR,NZ),W1(NR,NZ)
     1,W2(NR,NZ),W3(NR,NZ),W4(NR,NZ),GA(NZ)
C     PROGRAM READS A DATA FILE AT TIMESTEP IT AND TIME TIM.
101   FORMAT(I3,21F6.0)
102   FORMAT(20F6.0)
103   FORMAT(I3,21F6.3)
104   FORMAT(20F6.3)
105   FORMAT(I3,21F6.1)
106   FORMAT(20F6.1)
      DO 110 J=1,NZ
      READ(7,101)JJ,(T(I,J),I=1,21)
C     READ(7,102)(T(I,J),I=22,41)
110   CONTINUE
      DO 120 J=1,NZ
      READ(7,103)JJ,(Y(I,J),I=1,21)
C     READ(7,104)(Y(I,J),I=22,41)
120   CONTINUE
      DO 130 J=1,NZ
      READ(7,103)JJ,(R(I,J),I=1,21)
C     READ(7,104)(R(I,J),I=22,41)
130   CONTINUE
      DO 140 J=1,NZ
      READ(7,105)JJ,(U(I,J),I=1,21)
C     READ(7,106)(U(I,J),I=22,41)
140   CONTINUE
      DO 160 J=1,NZ
      IF(J.LT.28) THEN
      GA(J)=GAR
      ELSE
      GA(J)=0.
      END IF
      DO 150 I=1,NR
      W3(I,J)=T(I,J)
      W2(I,J)=Y(I,J)
      W1(I,J)=R(I,J)
      W4(I,J)=U(I,J)
150   CONTINUE
160   CONTINUE
      RETURN
      END
      SUBROUTINE INITIAL(TA,T,Y,R,NR,NZ,GA,W2,W3,W4,U)
      DIMENSION T(21,151),R(21,151),Y(21,151),GA(151),W2(21,151)
     1,W3(21,151),U(21,151),W4(21,151)
      DO 20 I=1,NR
      DO 18 J=1,NZ
      U(I,J)=0.
      W4(I,J)=0.
      IF(J.LT.9) THEN
      R(I,J)=.999
      ELSE
      R(I,J)=1.0
      END IF
      IF(J.LT.6) THEN
      Y(I,J)=.01
      W2(I,J)=.01
      ELSE IF (J.EQ.6) THEN
      Y(I,J)=.01
      W2(I,J)=.01
      ELSE IF(J.EQ.7) THEN
      Y(I,J)=.02
      W2(I,J)=.02
      ELSE IF (J.EQ.8) THEN
      Y(I,J)=.04
      W2(I,J)=.04
      ELSE IF(J.EQ.9) THEN
      Y(I,J)=.08
      W2(I,J)=.08
      ELSE IF (J.EQ.10) THEN
      Y(I,J)=.16
      W2(I,J)=.16
      ELSE
      Y(I,J)=.232
      W2(I,J)=.232
      END IF
      IF(J.LT.6) THEN
      T(I,J)=1000.
      W3(I,J)=1000.
      ELSE IF(J.GE.6.AND.J.LE.9) THEN
      T(I,J)=1000.-140.*(J-5)
      W3(I,J)=T(I,J)
      ELSE
      T(I,J)=TA
      W3(I,J)=TA
      END IF
18    CONTINUE
20    CONTINUE
      DO 22 J=1,NZ
      GA(J)=0.
22    CONTINUE
      RETURN
      END
      SUBROUTINE REACT(T,R,NR,NZ,W1,B,D1,Y,TS,E,W2,W3,RR,K1,RRW)
      DIMENSION T(21,151),R(21,151),W1(21,151),Y(21,151)
     1,W2(21,151),W3(21,151),RR(21,151),RRW(21,151)
C     CALCULATES REACTION RATE/MAX CHAR DENSITY(RR/DCMAX)
      DO 20 I=1,NR
      DO 18 J=1,NZ
      IF(K1.EQ.1) THEN
      RR(I,J)=B*R(I,J)*Y(I,J)*EXP(-E/T(I,J))/D1
      RRW(I,J)=RR(I,J)
      ELSE
      RRW(I,J)=B*W1(I,J)*W2(I,J)*EXP(-E/W3(I,J))/D1
      END IF
      W1(I,J)=R(I,J)-(RRW(I,J)+RR(I,J))*TS/2.
      IF(W1(I,J).LT.0) W1(I,J)=0.
18    CONTINUE
20    CONTINUE
      RETURN
      END
      SUBROUTINE TEMP(NG,A,B,C,D1,D2,NR,NZ,PH,TS,E,T,H1,TA,R,Y
     1,RR,W3,U,W4,SPHGS,RRW,ISKIP,W,A1,A2,A3)
      DIMENSION T(21,151),R(21,151),Y(21,151),S(21,151),RR(21,151)
     1,W3(21,151),U(21,151),W4(21,151),RRW(21,151)
      DT(A1,A2,TT)=A1+A2*TT**3
      CC=1.-W
      GM1=A*TS*NG*NG/(2.*(1-PH))
      A4=A3*GM1
      TT=300.
      HH=H1*DT(A1,A2,TT)
      B1=C*D2*TS/2.
      GD=PH*SPHGS*NG*TS/(4.*D1*(1.-PH))
      IF(ISKIP.EQ.2)GO TO 131
      DO 100 I=2,NR-1
      GPL=1.+1./(2.*(I-1))
      GMI=1.-1./(2.*(I-1))
      DO 95 J=2,NZ-1
      TT=T(I,J)
      GM=GM1*DT(A1,A2,TT)
      S(I,J)=(1.-4.*GM)*T(I,J)+GM*(T(I,J+1)+T(I,J-1)+GPL*T(I+1,J)
     1+GMI*T(I-1,J))+B1*RR(I,J)-GD*U(I,J)*(T(I+1,J)-T(I-1,J))
     2+A4*(T(I,J)*(T(I+1,J)-T(I-1,J)+T(I,J+1)-T(I,J-1)))**2
95    CONTINUE
100   CONTINUE
      TT=T(1,1)
      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)
      S(1,1)=(1.-6.*GM-GM*2.*H/NG)*T(1,1)+2.*GM*(T(1,2)+2.*T(2,1)
     1+H*TA/NG)+B1*RR(1,1)+A4*(T(1,1)*2.*H*(T(1,1)-TA)/NG)**2
      TT=T(1,NZ)
      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)

      S(1,NZ)=(1.-6.*GM-2.*GM*H/NG)*T(1,NZ)+4.*GM*T(2,NZ)
     1+2.*GM*T(1,NZ-1)+GM*2.*H*TA/NG+B1*RR(1,NZ)
     2+A4*(T(1,NZ)*2.*H*(T(1,NZ)-TA)/NG)**2
      GPL=1.+1./(2.*(NR-1))
      TT=T(NR,1)
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      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)
      S(NR,1)=(1.-4.*GM-(2.+2.*GPL)*GM*H/NG)*T(NR,1)+GM*(2.*
     1T(NR-1,1)+2.*T(NR,2))+(2.+2.*GPL)*GM*H*TA/NG+B1*RR(NR,1)
     2+GD*U(NR,1)*(2.*H*(T(NR,1)-TA)/NG)
      TT=T(NR,NZ)
      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)
      S(NR,NZ)=(1.-4.*GM-(2.+2.*GPL)*GM*H/NG)*T(NR,NZ)+GM*(2.*
     1T(NR-1,NZ)+2.*T(NR,NZ-1))+(2.+2.*GPL)*GM*H*TA/NG+B1*RR(NR,NZ)
     2+GD*U(NR,NZ)*(2.*H*(T(NR,NZ)-TA)/NG)
     3+A4*(T(NR,NZ)*4.*H*(T(NR,NZ)-TA)/NG)**2
      DO 120 I=2,NR-1
      GPL=1.+1./(2.*(I-1))
      GMI=1.-1./(2.*(I-1))
      TT=T(I,1)
      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)
      S(I,1)=(1.-4.*GM-2.*GM*H/NG)*T(I,1)+GM*(GPL*T(I+1,1)
     1+GMI*T(I-1,1))+2.*GM*T(I,2)+2.*GM*H*TA/NG
     2+B1*RR(I,1)-GD*U(I,1)*(T(I+1,1)-T(I-1,1))
     3+A4*(T(I,1)*(T(I+1,1)-T(I-1,1)+2.*H*(T(I,1)-TA)/NG))**2
      TT=T(I,NZ)
      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)
      S(I,NZ)=(1.-4.*GM-2.*GM*H/NG)*T(I,NZ)+GM*(GPL*T(I+1,NZ)
     1+GMI*T(I-1,NZ)+2.*T(I,NZ-1))+2.*GM*H*TA/NG+B1*RR(I,NZ)
     2-GD*U(I,NZ)*(T(I+1,NZ)-T(I-1,NZ))
     3+A4*(T(I,NZ)*(T(I+1,NZ)-T(I-1,NZ)-2.*H*(T(I,NZ)-TA)/NG))**2
120   CONTINUE
      GPL=1.+1./(2.*(NR-1))
      DO 130 J=2,NZ-1
      TT=T(1,J)
      GM=GM1*DT(A1,A2,TT)
      S(1,J)=(1.-6.*GM)*T(1,J)+GM*(T(1,J+1)+T(1,J-1)+4.*T(2,J))
     1+B1*RR(1,J)+A4*(T(1,J)*(T(1,J+1)-T(1,J-1)))**2
      TT=T(NR,J)
      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)
      S(NR,J)=(1.-4.*GM-2.*GM*H*GPL/NG)*T(NR,J)+GM*(2.*T(NR-1,J)
     1+T(NR,J+1)+T(NR,J-1))+2.*GM*H*TA*GPL/NG
     2+B1*RR(NR,J)+GD*U(NR,J)*(2.*H*(T(NR,J)-TA)/NG)
     3+A4*(T(NR,J)*(-2.*H*(T(NR,J)-TA)/NG+T(I,J+1)-T(I,J-1)))**2
130   CONTINUE
131   CONTINUE
      DO 140 I=1,NR
      IF(I.GT.1) THEN
      GPL=1.+1./(2.*(I-1))
      GMI=1.-1./(2.*(I-1))
      END IF
      DO 138 J=1,NZ
      TT=W3(I,J)
      GM=GM1*DT(A1,A2,TT)
      H=HH/DT(A1,A2,TT)
      IF(I.GT.1.AND.I.LT.NR.AND.J.GT.1.AND.J.LT.NZ) THEN
      VAL=(GM*(GPL*W3(I+1,J)+GMI*W3(I-1,J)+W3(I,J+1)+W3(I,J-1))
     1+S(I,J)+B1*RRW(I,J)-GD*W4(I,J)*(W3(I+1,J)-W3(I-1,J))
     2+A4*(W3(I,J)*(W3(I+1,J)-W3(I-1,J)+W3(I,J+1)-W3(I,J-1)))**2
     3)/(1.+4.*GM)
      ELSE IF(J.EQ.1.AND.I.LT.NR.AND.I.GT.1) THEN
      VAL=(GM*(2.*W3(I,2)+GPL*W3(I+1,1)+GMI*W3(I-1,1)+2.*H*TA/NG)
     1+S(I,1)+B1*RRW(I,J)-GD*W4(I,1)*(W3(I+1,1)-W3(I-1,1))
     2+A4*(W3(I,J)*(W3(I+1,J)-W3(I-1,J)+2.*H*(W3(I,J)-TA)/NG))**2
     3)/(1.+4.*GM+2.*H*GM/NG)
      ELSE IF(J.LT.NZ.AND.J.GT.1.AND.I.EQ.NR) THEN
      VAL=(GM*(2.*W3(NR-1,J)+W3(NR,J+1)+W3(NR,J-1)+2.*H*TA*GPL/NG)
     1+S(NR,J)+B1*RRW(I,J)-GD*W4(NR,J)*2.*H*TA/NG
     2+A4*(W3(I,J)*(-2.*H*(W3(I,J)-TA)/NG+W3(I,J+1)-W3(I,J-1)))**2
     3)/(1.+4.*GM+2.*GM*GPL*H/NG-GD*W4(NR,J)*2.*H/NG)
      ELSE IF (I.EQ.1.ANC.J.LT.NZ.AND.J.GT.1) THEN
      VAL=(GM*(4.*W3(I+1,J)+W3(I,J+1)+W3(I,J-1))+S(I,J)+B1*RRW(I,J)
     1+A4*(W3(I,J)*(W3(I,J+1)-W3(I,J-1)))**2
     2)/(1.+6.*GM)
      ELSE IF(J.EQ.NZ.AND.I.LT.NR.AND.I.GT.1) THEN
      VAL=(GM*(GPL*W3(I+1,J)+GMI*W3(I-1,J)+2.*W3(I,J-1)+2.*H*TA/NG
     1)+S(I,J)+B1*RRW(I,J)-GD*W4(I,J)*(W3(I+1,J)-W3(I-1,J))
     2+A4*(W3(I,J)*(W3(I+1,J)-W3(I-1,J)-2.*H*(W3(I,J)-TA)/NG))**2
     3)/(1.+4.*GM+2.*GM*H/NG)
      ELSE IF (J.EQ.1.AND.I.EQ.1) THEN
      VAL=(GM*(4.*W3(I+1,J)+2.*W3(I,J+1)+2.*H*TA/NG)+S(I,J)+B1
     1*RRW(I,J)+A4*(W3(I,J)*2.*H*(W3(I,J)-TA)/NG)**2
     2)/(1.+6.*GM+2.*GM*H/NG)
      ELSE IF(I.EQ.1.AND.J.EQ.NZ) THEN
      VAL=(GM*(4.*W3(I+1,J)+2.*W3(I,J-1)+2.*H*TA/NG)+S(I,J)
     1+B1*RRW(I,J)+A4*(W3(I,J)*2.*H*(W3(I,J)-TA)/NG)**2
     2)/(1.+6.*GM+2.*GM*H/NG)
      ELSE IF (J.EQ.1.AND.I.EQ.NR) THEN
      VAL=(GM*(2.*W3(I-1,J)+2.*W3(I,J+1)+(2.+2.*GPL)*H*TA/NG)
     1+S(I,J)+B1*RRW(I,J)-GD*W4(I,J)*2.*H*TA/NG)
     2/(1.+4.*GM+(2.+2.*GPL)*GM*H/NG-GD*W4(I,J)*2.*H/NG)
      ELSE IF (I.EQ.NR.AND.J.EQ.NZ) THEN
      VAL=(GM*(2.*W3(I-1,J)+2.*W3(I,J-1)+(2.+2.*GPL)*H*TA/NG)
     1+S(I,J)+B1*RRW(I,J)-GD*W4(I,J)*2.*H*TA/NG
     2+A4*(W3(I,J)*4.*H*(W3(I,J)-TA)/NG)**2
     3)/(1.+4.*GM+(2.+2.*GPL)*GM*H/NG-GD*W4(I,J)*2.*H/NG)
      END IF
      W3(I,J)=W*VAL+CC*W3(I,J)
138   CONTINUE
140   CONTINUE
      RETURN
      END
      SUBROUTINE OXY(NG,D,TS,PH,B,AN,E,D2,CN,Y,T,R,GAR,W2
     1,NR,NZ,GA,TP,YA,RR,D1,U,W4,RRW,W3,TA,ISKIP,GARP,W)
      DIMENSION Y(21,151),T(21,151),R(21,151),GA(151),C(21,151)
     1,W2(21,151),RR(21,151),U(21,151),W4(21,151),RRW(21,151),W3(21,151)
      GM1=TS*NG*NG/2.
      BB=TS*(1.-PH)*D1*D2/(2.*PH)
      CC=1.-W
      GV=NG*TS/4.
      IF(ISKIP.EQ.2)GO TO 21
      DO 20 I=1,NR
      IF(I.GT.1) THEN
      GPL=1.+1./(2.*(I-1))
      GMI=1.-1./(2.*(I-1))
      END IF
      DO 10 J=1,NZ
      IF(I.GT.1.AND.I.LT.NR.AND.J.GT.1.AND.J.LT.NZ) THEN
      GM=GM1*DC(I,J,T,D)
      CM=1.-4.*GM
      C(I,J)=CM*Y(I,J)+GM*(Y(I,J+1)
     1+Y(I,J-1)+GPL*Y(I+1,J)+GMI*Y(I-1,J))-BB*(Y(I,J)*(1.-AN)+CN)
     2*RR(I,J)-GV*U(I,J)*(Y(I+1,J)-Y(I-1,J))
      ELSEIF(J.EQ.NZ.AND.I.GT.1.AND.I.LT.NR)THEN
      GM=GM1*DC(I,J,T,D)
      CM=1.-4.*GM
      C(I,J)=CM*Y(I,J)+GM*(2.*
     1Y(I,J-1)+GPL*Y(I+1,J)+GMI*Y(I-1,J))-BB*(Y(I,J)*(1.-AN)+CN)
     2*RR(I,J)-GV*U(I,J)*(Y(I+1,J)-Y(I-1,J))
      ELSE IF (J.EQ.1.AND.I.GT.1.AND.I.LT.NR) THEN
      GM=GM1*DC(I,J,T,D)
      CM=1.-4.*GM
      DF=GM/GM1
      C(I,J)=CM*Y(I,J)+GM*(2.*Y(I,J+1)+2.*GAR*(YA-Y(I,J))
     1/(DF*NG)+GPL*Y(I+1,J)+GMI*Y(I-1,J))-BB*(Y(I,J)
     2*(1.-AN)+CN)*RR(I,J)-GV*U(I,J)*(Y(I+1,J)-Y(I-1,J))
      ELSE IF (I.EQ.1.AND.J.GT.1.AND.J.LT.NZ) THEN
      GM=GM1*DC(I,J,T,D)
      C(I,J)=(1.-6.*GM)*Y(I,J)+GM*(Y(I,J+1)
     1+Y(I,J-1)+4.*Y(I+1,J))-BB*(Y(I,J)*(1.-AN)+CN)*RR(I,J)
      ELSE IF(I.EQ.NR.AND.J.GT.1.AND.J.LT.NZ) THEN
      GM=GM1*DC(I,J,T,D)
      CM=1.-4.*GM
      DF=GM/GM1
      IF(GA(J).EQ.0) THEN
      C(I,J)=CM*Y(I,J)+GM*(Y(I,J+1)+Y(I,J-1)+2.*Y(I-1,J)
     1+2.*GARP*GPL*(YA-Y(I,J))/(DF*NG))+2.*GPL*U(I,J)*Y(I,J)/(DF*NG)
     2-BB*(Y(I,J)*(1.-AN)+CN)*RR(I,J)
     3-GV*U(I,J)*2.*GARP*(YA-Y(I,J))/(DF*NG)
      ELSE
      C(I,J)=CM*Y(I,J)+GM*(Y(I,J+1)+Y(I,J-1)+2.*Y(I-1,J)+2.*GAR*
     1GPL*(YA-Y(I,J))/(DF*NG))+2.*GPL*U(I,J)*Y(I,J)/(DF*NG)-BB
     2*(Y(I,J)*(1.-AN)+CN)*RR(I,J)-GV*U(I,J)*2.*GAR*(YA-Y(I,J))
     3/(DF*NG)
      END IF
      ELSE IF (I.EQ.1.AND.J.EQ.1) THEN
      GM=GM1*DC(I,J,T,D)
      DF=GM/GM1
      C(I,J)=(1.-6.*GM)*Y(I,J)+GM*(2.*Y(I,J+1)+2.*GAR*(YA-Y(I,J))/
     1(DF*NG)+4.*Y(I+1,J))-BB*(Y(I,J)*(1.-AN)+CN)*RR(I,J)
      ELSE IF(I.EQ.1.AND.J.EQ.NZ) THEN
      GM=GM1*DC(I,J,T,D)
      C(I,J)=(1.-6.*GM)*Y(I,J)+GM*(2.*Y(I,J-1)+4.*Y(I+1,J))-BB
     1*(Y(I,J)*(1.-AN)+CN)*RR(I,J)
      ELSE IF(I.EQ.NR.AND.J.EQ.1) THEN
      GM=GM1*DC(I,J,T,D)
      CM=1.-4.*GM
      DF=GM/GM1
      C(I,J)=CM*Y(I,J)+GM*(2.*Y(I,J+1)+2.*Y(I-1,J)+GAR*
     1(2.+2.*GPL)*(YA-Y(I,J))/(DF*NG))+2.*GPL*U(I,J)*Y(I,J)/(DF*NG)
     2-BB*(Y(I,J)*(1.-AN)+CN)*RR(I,J)-GV*U(I,J)*2.*GAR*(YA-Y(I,J))
     3/(DF*NG)
      ELSE IF (I.EQ.NR.AND.J.EQ.NZ) THEN
      GM=GM1*DC(I,J,T,D)
      CM=1.-4.*GM
      DF=GM/GM1
      C(I,J)=CM*Y(I,J)+GM*(2.*Y(I,J-1)+2.*Y(I-1,J))-BB
     1*(Y(I,J)*(1.-AN)+CN)*RR(I,J)-GV*U(I,J)*2.*GAR*(YA-Y(I,J))
     2/(DF*NG)
      END IF
10    CONTINUE
20    CONTINUE
21      CONTINUE
      DO 50 I=1,NR
      IF (I.GT.1) THEN
      GPL=1.+1./(2.*(I-1))
      GMI=1.-1./(2.*(I-1))
      END IF
      DO 40 J=1,NZ
      IF (I.GT.1.AND.I.LT.NR.AND.J.GT.1.AND.J.LT.NZ) THEN
      GM=GM1*DN(I,J,W3,D)
      CP=1.+4.*GM
      VAL=W*(GM*(W2(I,J+1)+W2(I,J-1)+GPL*W2(I+1,J)+GMI*W2(I-1,J))
     1-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J)
     2+C(I,J)-GV*W4(I,J)*(W2(I+1,J)-W2(I-1,J)))/CP
      ELSEIF(J.EQ.NZ.AND.I.GT.1.AND.I.LT.NR) THEN
      GM=GM1*DN(I,J,W3,D)
      CP=1.+4.*GM
      VAL=W*(GM*(2.*W2(I,NZ-1)+GPL*W2(I+1,NZ)+GMI*W2(I-1,NZ))
     1-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J)
     2+C(I,NZ)-GV*W4(I,J)*(W2(I+1,J)-W2(I-1,J)))/CP
      ELSE IF(J.EQ.1.AND.I.GT.1.AND.I.LT.NR) THEN
      GM=GM1*DN(I,J,W3,D)
      CP=1.+4.*GM
      DF=GM/GM1
      VAL=W*(GM*(2.*W2(I,2)+2.*GAR*YA/(DF*NG)+GPL*W2(I+1,1)+GMI*
     1W2(I-1,1))+C(I,1)-GV*W4(I,J)*(W2(I+1,J)-W2(I-1,J))
     2-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))/(CP+2.*GAR*GM/(DF*NG))
      ELSE IF(I.EQ.1.AND.J.GT.1.AND.J.LT.NZ) THEN
      GM=GM1*DN(I,J,W3,D)
      CP=1.+4.*GM
      VAL=W*(GM*(W2(1,J+1)+W2(1,J-1)+4.*W2(2,J))+C(1,J)
     1-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))/(1.+6.*GM)
      ELSE IF(I.EQ.NR.AND.J.GT.1 AND.J.LT.NZ) THEN
      GM=GM1*DN(I,J,W3,D)
      CP=1.+4.*GM
      DF=GM/GM1
      IF(GA(J).EQ.0) THEN
      IF(T(NR,J).LT.TP) THEN
      VAL=W*(GM*(W2(NR,J+1)+W2(NR,J-1)+2.*W2(NR-1,J)
     1+GPL*2.*GARP*YA/(DF*NG))+C(NR,J)
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     2-GV*W4(I,J)*2.*GARP*YA/(DF*NG)
     3-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))/(CP-2.*GPL*GM*W4(I,J)/(DF*NG)
     4+GPL*2.*GARP*GM/(DF*NG)-GV*W4(I,J)*2.*GARP/(DF*NG))
      ELSE
      GA(J)=GAR
      VAL=W*(GM*(W2(NR,J+1)+W2(NR,J-1)+2.*W2(NR-1,J)+GPL*2.*GAR*YA
     1/(DF*NG))+C(NR,J)-GV*W4(I,J)*2.*GAR*YA/(DF*NG)
     2-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))
     3/(CP+GPL*2.*GAR*GM/(DF*NG)-2.*GPL*GM*W4(I,J)/(DF*NG)
     4-GV*W4(I,J)*2.*GAR/(DF*NG))
      END IF
      ELSE
      VAL=W*(GM*(W2(NR,J+1)+W2(NR,J-1)+2.*W2(NR-1,J)+GPL*2.*GAR*YA
     1/(DF*NG))+C(NR,J)-GV*W4(I,J)*2.*GAR*YA/(DF*NG)
     2-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))
     3/(CP+GPL*2.*GAR*GM/(DF*NG)-2.*GPL*GM*W4(I,J)/(DF*NG)
     4-GV*W4(I,J)*2.*GAR/(DF*NG))
      END IF
      ELSE IF(I.EQ.1.AND.J.EQ.1) THEN
      GM=GM1*DN(I,J,W3,D)
      DF=GM/GM1
      VAL=W*(GM*(2.*W2(I,J+1)+2.*GAR*YA/(DF*NG)+4.*W2(I+1,J))+
     1C(I,J)-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))/(1.+6.*GM+2.*GAR*GM
     2/(DF*NG))
      ELSE IF(I.EQ.1.AND.J.EQ.NZ) THEN
      GM=GM1*DN(I,J,W3,D)
      VAL=W*(GM*(2.*W2(I,J-1)+4.*W2(I+1,J))+C(I,J)
     1-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))/(1.+6.*GM)
      ELSE IF (I.EQ.NR.AND.J.EQ.1) THEN
      GM=GM1*DN(I,J,W3,D)
      CP=1.+4.*GM
      DF=GM/GM1
      VAL=W*(GM*(2.*W2(I,J+1)+2.*W2(I-1,J)+(2.+2.*GPL)*GAR*YA/(DF*NG))+
     1C(I,J)-GV*W4(I,J)*2.*GAR*YA/(DF*NG)-BB*(W2(I,J)*(1.-AN)+CN)
     2*RRW(I,J))/(CP+(2.+2.*GPL)*GAR*GM/(DF*NG)-GV*W4(I,J)
     3*2.*GAR/(DF*NG)-2.*GPL*GM*W4(I,J)/(DF*NG))
      ELSE IF(I.EQ.NR.AND.J.EQ.NZ) THEN
      GM=GM1*DN(I,J,W3,D)
      CP=1.+4.*GM
      VAL=W*(GM*(2.*W2(I,J-1)+2.*W2(I-1,J))+C(I,J)
     1-BB*(W2(I,J)*(1.-AN)+CN)*RRW(I,J))/CP
      END IF
C     W IS MISSING IN FRONT OF VAL SINCE IT IS INCLUDED EARLIER IN EQ
      W2(I,J)=VAL+CC*W2(I,J)
40    CONTINUE
50    CONTINUE
      YNEG=0.
      DO 60 I=1,NR
      DO 55 J=1,NZ
      IF(W2(I,J).LT.0.) THEN
C     IF(W2(I,J).LT.YNEG) YNEG=W2(I,J)
      W2(I,J)=0.
      END IF
55    CONTINUE
60    CONTINUE
      RETURN
      END
      SUBROUTINE VELOCR(PH,AN,D1,D2,NG,NR,NZ,RR,W4,U,RRW)
      DIMENSION RR(21,151),W4(21,151),U(21,151),RRW(21,151)
C     CALCULATES RADIAL VELOCITY DIVIDED BY R0 (W4/R0)
C     ASSUMES CONSTANT GAS DENSITY.
C     INTEGRATION IS DONE BY THE TRAPEZOID RULE
      DO 20 J=1,NZ
      DO 10 I=2,NR
      W4(I,J)=(1.-PH)*(1.-AN)*D1*D2*((I-2)*RR(I-1,J)+(I-1)*RR(I,J))/
     1(2.*PH*NG*(I-1))+W4(I-1,J)*(I-2)/(I-1)
10    CONTINUE
20    CONTINUE
      RETURN
      END
      FUNCTION DC(I,J,T,D)
      DIMENSION T(21,151)
      DC=D*(T(I,J)/273.)**1.75
      RETURN
      END
      FUNCTION DN(I,J,W3,D)
      DIMENSION W3(21,151)
      DN=D*(W3(I,J)/273.)**1.75
      RETURN
      END
      SUBROUTINE OUTPUTP(D,A,B,C,E,D1,D2,PH,TP,GAR,GARP,AN,CN,H,NG
     1,RIZR,IN,TS,TIM)
      WRITE(6,104)D,A,B,C
      WRITE(6,105)E,D1,D2,PH
102   FORMAT('TIME STEP =',E9.3,'TIME =',E9.3)
103   FORMAT('POINTS IN R = ',I3,' POINTS IN Z = ',I3)
104   FORMAT('D=',E9.3,'A=',E9.3,'B=',E9.3,'C=',E9.3)
105   FORMAT('E=',E9.3,'D1=',E9.3,'D2=',E9.3,'PH=',E9.3)
106   FORMAT('GAR=',E9.3,'GARP=',E9.3,'AN=',E9.3,'CN=',E9.3)
107   FORMAT('TP=',E9.3,'H=',E9.3,'NG=',I3,'RIZR=',F6.2,'IN=',I3)
      WRITE(6,106)GAR,GARP,AN,CN
      WRITE(6,107)TP,H,NG,RIZR,IN
      WRITE(6,102)TS,TIM
      WRITE(6,103)NG+1,NG*RIZR+1
      RETURN
      END
      SUBROUTINE OUTPUT(NR,NZ,T,Y,R,U)
      DIMENSION T(21,151),R(21,151),Y(21,151),U(21,151)
101   FORMAT(I3,21F6.1)
102   FORMAT(I3,21F6.3)
103   FORMAT(I3,21F6.0)
104   FORMAT(3X,20F6.1)
105   FORMAT(3X,20F6.3)
106   FORMAT(3X,20F6.0)
121   FORMAT('TEMPERATURE')
122   FORMAT('OXYGEN')
123   FORMAT('DENSITY FRACTION')
124   FORMAT('RADIAL VELOCITY')
      WRITE(6,121)
      DO 175 J=1,NZ
      WRITE(6,103)J,(T(I,J),I=1,21)
C     WRITE(6,106)(T(I,J),I=22,41)
175   CONTINUE
      WRITE(6,122)
      DO 180 J=1,NZ
      WRITE(6,102)J,(Y(I,J),I=1,21)
C     WRITE(6,105)(Y(I,J),I=22,41)
180   CONTINUE
      WRITE (6,123)
      DO 190 J=1,NZ
      WRITE(6,102)J,(R(I,J),I=1,21)
C     WRITE(6,105)(R(I,J),I=22,41)
190   CONTINUE
      WRITE(6,124)
      DO 200 J=1,NZ
      WRITE(6,101)J,(U(I,J),I=1,21)
C     WRITE(6,104)(U(I,J),I=22,41)
200   CONTINUE
      RETURN
      END
      SUBROUTINE TRAPE(I,J,T,W3,NR,NZ,TS,PH,A,H,R,Y,E,TA
     1,B,C,D1,D2)
      DIMENSION T(21,151),W3(21,151),Y(21,151),R(21,151)
C     W3 IS THE TEMP. AT THE PRESENT TIMESTEP.
C     T IS THE TEMPERATURE AT THE LAST TIMESTEP.
C     INTEGRATION METHOD RESEMBLES TRAPEZOID METHOD IN THAT THE
C     CYLINDER IS DIVIDED UP INTO SMALL CONSTANT TEMP. PIECES.
C     VOLUME INTEGRALS
       NG=NR-1
      H1=0
      H2=0
      H3=0
      H4=0
      DO 20 I=2,NR-1
      DO 10 J=2,NZ-1
      H4 =H4+2.*(I-1)*(T(I,J)-TA)
      H1=H1+2.*(I-1)*(W3(I,J)-T(I,J))
10    H3=H3+2.*(I-1)*R(I,J)*Y(I,J)*EXP(-E/W3(I,J))
20    CONTINUE
      DO 30 J=2,NZ-1
      H4=H4+NG*(T(NR,J)-TA)
      H1=H1+NG*(W3(NR,J)-T(NR,J))
30    H3=H3+NG*R(NR,J)*Y(NR,J)*EXP(-E/W3(I,J))
      DO 40 I=2,NR-1
      H4=H4+(I-1)*(T(I,1)-TA+T(I,NZ)-TA)
      H1=H1+(I-1)*(W3(I,1)-T(I,1)+W3(I,NZ)-T(I,NZ))
40    H3=H3+(I-1)*(R(I,1)*Y(I,1)*EXP(-E/W3(I,1))+R(I,NZ)*
     1Y(I,NZ)*EXP(-E/W3(I,NZ)))
      DO 50 J=2,NZ-1
      H4=H4+.25*(T(1,J)-TA)
      H1=H1+.25*(W3(1,J)-T(1,J))
50    H3=H3+.25*R(1,J)*Y(1,J)*EXP(-E/T(1,J))
      H4=H4+.5*NG*(T(NR,1)-TA+T(NR,NZ)-TA)
      H1=H1+.5*NG*(W3(NR,1)-T(NR,1)+W3(NR,NZ)-T(NR,NZ))
      H3=H3+.5*NG*(R(NR,1)*Y(NR,1)*EXP(-E/W3(NR,1))+R(NR,NZ)*
     1Y(NR,NZ)*EXP(-E/W3(NR,NZ)))
      H4=H4+(T(1,1)-TA+T(1,NZ)-TA)/8.
      H1=H1+(W3(1,1)-T(1,1)+W3(1,NZ)-T(1,NZ))/8.
      H3=H3+(R(1,1)*Y(1,1)*EXP(-E/T(1,1))+R(1,NZ)*Y(1,NZ)
     1*EXP(-E/W3(1,NZ)))/8.
      H4=H4*(1.-PH)
      H1=H1*(1.-PH)
      H3=H3*(1.-PH)*C*D2*B*TS/D1
C     SURFACE INTEGRALS
      H2Z=0.
      DO 60 J=1,NZ
      IF (J.GT.1.AND.J.LT.NZ) THEN
      H2Z=H2Z+(W3(NR,J)+T(NR,J)-2.*TA)/2.
      ELSE
      H2Z=H2Z+(W3(NR,J)+T(NR,J)-2.*TA)/4.
      END IF
60    CONTINUE
      H2=H2Z*2.*TS*NG*NG*A*H
C     TOP SURFACE
      H2R=0.
      DO 70 I=2,NR-1
70    H2R=H2R+2.*(I-1)*(W3(I,1)+T(I,1)-2.*TA)/2.
      H2R=H2R+.25*(W3(1,1)+T(1,1)-2.*TA)/2.+NG*(W3(NR,1)+T(NR,1)
     1-2.*TA)/2.
      H2=H2R*A*H*TS*NG+H2
C     BOTTOM SURFACE
      H2R=0.
      DO 80 I=2,NR-1
80    H2R=H2R+2.*(I-1)*(W3(I,NZ)+T(I,NZ)-2.*TA)/2.
      H2R=H2R+.25*(W3(1,NZ)+T(1,NZ)-2.*TA)/2.+NG*(W3(NR,NZ)
     1+T(NR,NZ)-2.*TA)/2.
      H2=H2+A*H*TS*NG*H2R
      WRITE(6,100)
100   FORMAT('VALUE OF THE HEAT INTEGRALS ARE:')
      WRITE(6,101)H1,H2,H3
101   FORMAT('VOLUME TERM H1=',F9.3,'CONVECTION H2=',F9.3,'SOURCE
     1 H3= ',F9.3)
      WRITE(6,102) H4
102   FORMAT('TOTAL HEAT CONTAINED IN SOLID',F9.3)
      WRITE(6,103) 100.*(H1+H2-H3)/H4
103   FORMAT('% HEAT UNACCOUNTED FOR IN CALCULATIONS',F9.3)
      RETURN
      END
      SUBROUTINE OTRAPE(I,J,T,W3,NR,NZ,TS,PH,CN,GAR,R,Y,E,TA,
     1B,C,GA,W2,YA)
      DIMENSION T(21,151),W3(21,151),Y(21,151),W2(21,151),R(21,151)
     1,GA(151)
C     W2 IS THE OXYGEN CONCENTRATION AT THE PRESENT TIMESTEP
C     Y IS THE OXYGEN CONCENTRATION AT THE LAST TIMESTEP
C     INTEGRATION IS IDENTICAL TO THAT IN TRAPE
C     VOLUME INTEGRATION
      NG=NR-1
      H1=0
      H2=0
      H3=0
```

```
      H4=0
      DO 20 I=2,NR-1
      DO 10 J=2,NZ-1
      H4=H4+2.*(I-1)*(Y(I,J)-YA)
      H1=H1+2.*(I-1)*(W2(I,J)-Y(I,J))
10    H3=H3+2.*(I-1)*R(I,J)*Y(I,J)*EXP(-E/W3(I,J))
20    CONTINUE
      DO 30 J=2,NZ-1
      H4=H4+NG*(Y(NR,J)-YA)
      H1=H1+NG*(W2(NR,J)-Y(NR,J))
30    H3=H3+NG*R(NR,J)*Y(NR,J)*EXP(-E/W3(NR,J))
      DO 40 I=2,NR-1
      H4=H4+(I-1)*(Y(I,1)+Y(I,NZ)-2.*YA)
      H1=H1+(I-1)*(W2(I,1)-Y(I,1)+W2(I,NZ)-Y(I,NZ))
40    H3=H3+(I-1)*(R(I,1)*Y(I,1)*EXP(-E/W3(I,1))+R(I,NZ)
     1*Y(I,NZ)*EXP(-E/W3(I,NZ)))
      DO 50 J=2,NZ-1
      H4=H4+.25*(Y(1,J)-YA)
      H1=H1+.25*(W2(1,J)-Y(1,J))
50    H3=H3+.25*Y(1,J)*EXP(-E/W3(1,J))
      H4=H4+.5*NG*(Y(NR,1)+Y(NR,NZ)-2.*YA)
      H1=H1+.5*NG *(W2(NR,1)+W2(NR,NZ)-Y(NR,1)-Y(NR,NZ))
      H3=H3+.5*NG*(R(NR,1)*Y(NR,1)*EXP(-E/W3(NR,1))+R(NR,NZ)*Y(NR,NZ)
     1*EXP(-E/W3(NR,NZ)))
      H4=H4+(Y(1,1)+Y(1,NZ)-2.*YA)/8.
      H1=H1+(W2(1,1)+W2(1,NZ)-Y(1,1)-Y(1,NZ))/8.
      H3=H3+(R(1,1)*Y(1,1)*EXP(-E/W3(1,1))+R(1,NZ)*Y(1,NZ)*
     1EXP(-E/W3(1,NZ)))/8.
      H3=H3*(1.-PH)*CN*B/PH
C     SURFACE INTEGRALS
      H2Z=0.
      DO 60 J=1,NZ
      IF(J.GT.1.AND.J.LT.NZ) THEN
      H2Z=H2Z+GA(J)*(W2(NR,J)+Y(NR,J)-2.*YA)/2.
      ELSE
      H2Z=H2Z+GA(J)*(W2(NR,J)+Y(NR,J)-2.*YA)/4.
      END IF
60    CONTINUE
      H2=H2Z*2.*NG*NG*TS
C     TOP SURFACE
      H2R=0.
      DO 70 I=2,NR-1
70    H2R=H2R+2.*GAR*(I-1)*(W2(I,1)+Y(I,1)-2.*YA)/2.
      H2R=H2R+.25*GAR*(W2(1,1)+Y(1,1)-2.*YA+NG*(W2(NR,1)+Y(NR,1)-
     12.*YA))/2.
      H2=H2+H2R*NG*TS
C     BOTTOM SURFACE NO DIFFUSION THROUGH THE FILTER
      WRITE(6,100)
100   FORMAT('VALUE OF THE OXYGEN INTEGRALS ARE:')
      WRITE(6,101)H1,H2,H3
101   FORMAT('VOLUME TERM H1=',F9.3,'CONVECTION H2 =',F9.3,'SOURCE
     1 H3= ',F9.3)
      WRITE(6,102) H4
102   FORMAT('TOTAL OXYGEN CONTAINED IN SOLID',F9.3)
      WRITE(6,103) 100.*(H1+H2-H3)/H4
103   FORMAT('% OXYGEN UNACCOUNTED FOR IN CALCULATIONS',F9.3)
      RETURN
      END
      SUBROUTINE TEST
      DIMENSION Y(21,151),R(21,151),T(21,151),GA(151),W2(21,151)
     1,RR(21,151),W3(21,151)
      PRINT*,'ENTER NR AND NZ'
      READ*, NR,NZ
      PRINT*,' NUMBER OF TIME STEPS'
      READ*,NTP
      NG=NR-1
      D=1.
      PRINT*,'ENTER NUMBER OF TIMESTEPS FOR OXYGEN BALANCE'
      READ*, IOB
      IOBN=0
      PRINT*,'ENTER TIME STEP'
      READ*,TS
10    PH=1
      B=1.
      AN=1.
      E=0.
      D1=220.
      D2=1.
      CN=1.
      GAR=2.
      TP=300
      YA=0.
      DO 20 I=1,NR
      DO 18 J=1,NZ
      GA(J)=2.
      T(I,J)=.00001
      W3(I,J)=.00001
      W2(I,J)=.00001
      R(I,J)=0.
      RR(I,J)=0.
      IF(J.EQ.1) THEN
      Y(I,J)=.00001
      ELSE
      Y(I,J)=0.00001
      END IF
18    CONTINUE
20    CONTINUE
      PRINT*,'ENTER I,J VALUES FOR Y(I,J)=100.
      READ*,I,J
      Y(I,J)=100.
      DO 60 K=1,NTP
      CALL OXY(NG,D,TS,PH,B,AN,E,D2,CN,Y,T,R,
     1GAR,W2,NR,NZ,GA,TP,YA,RR,D1)
      IOBN=IOBN+1
      IF(IOBN.EQ.IOB) THEN
      IOBN=0
      CALL OTRAPE(I,J,T,W3,NR,NZ,TS,PH,CN,GAR,R,Y,E,TA,B,C,GA,W2,YA)
      END IF
C     USE NEXT THREE STATEMENTS ONLY TO RUN Y=100. TEST CASE
C     DO 40 I=1,NR
C     Y(I,1)=100.
C     Y(I,NZ)=0.
40    CONTINUE
      IF(K.LT.NTP) THEN
      DO 30 I=1,NR
      DO 25 J=1,NZ
25    Y(I,J)=W2(I,J)
30    CONTINUE
      END IF
60    CONTINUE
      WRITE(6,101) NR,NZ
101   FORMAT('OXYG  NR = ',I4,' NZ = ',I4)
      WRITE(6,102) TS,NTP,TS*NTP
102   FORMAT('TIMESTEP = ',E9.3,' NUM STEPS=',I4,' TIME = ',E9.3)
      WRITE(6,104)
104   FORMAT('OXYGEN FOR LAST TIMESTEP')
      DO 80 J=1,NZ
      WRITE(6,100)J,(Y(I,J),I=1,NR)
80    CONTINUE
      WRITE(6,103)
103   FORMAT('OXYGEN FOR PRESENT TIMESTEP')
      DO 90 J=1,NZ
      WRITE(6,100)J,(W2(I,J),I=1,NR)
90    CONTINUE
100   FORMAT(I3,11(F9.3))
      RETURN
      END
      SUBROUTINE TESTT
C     TO TEST DIFFUSION PART OF CIG, THEN DO LOOP OVER Z MUST BE
C     RESET NOT TO INCLUDE Z=1 AND Z=NZ SUCH THAT THE TEMPERATURE
C     VALUES REMAIN 100 AND .001C. FAILURE TO DO THIS WILL LEAD TO
C     TEMPERATURE VALUES THAT ARE TOO LOW COMPARED TO THEORY.
      DIMENSION T(21,151),R(21,151),Y(21,151),W1(21,151),W2(21,151),
     1W3(21,151),GA(151),RR(21,151)
      PRINT*,'ENTER NR AND NZ'
      READ*,NR,NZ
      PRINT*,'ENTER NUMBER OF TIME STEPS'
      READ*,NTP
      PRINT*,'ENTER NUMBER OF TIMESTEPS FOR ENERGY BALANCE'
      READ*,IEB
      NG=NR-1
      IEBN=0
      A=1.
      PRINT*,'ENTER TIMESTEP'
      READ*,TS
      PH=.65
      D1=1.
      C=0.
      B=0.
      TA=0.
      D2=0.
      H=2.
      E=0.
      CN=0.
      YA=.232
      AN=0.
      GAR=5.
      ERR=.0001
      NTEST=1
      DO 5 J=1,NZ
5     GA(J)=0.
      DO 18 I=1,NR
      DO 20 J=1,NZ
      Y(I,J)=.232
      R(I,J)=0.
      RR(I,J)=0.
      W2(I,J)=.232
      W1(I,J)=0.
      IF(J.EQ.1) THEN
C     SET T AND W3=100. IN NEXT TWO LINES IF RUN T=100 CASE.
      T(I,J)=.00001
      W3(I,J)=.00001
      ELSE
      T(I,J)=.00001
      W3(I,J)=.00001
      END IF
20    CONTINUE
18    CONTINUE
      W3(11,11)=.00001
      PRINT*,'ENTER I,J VALUES FOR T(I,J)=100.
      READ*,I,J
      T(I,J)=100.
      DO 60 K=1,NTP
      CALL TEMP(NG,A,B,C,D1,D2,NR,NZ,PH,TS,E,T,H,TA,R,Y,RR,W3,ERR)
      IEBN=IEBN+1
      IF(IEBN.EQ.IEB) THEN
      IEBN=0
      CALL TRAPE(I,J,T,W3,NR,NZ,TS,PH,A,H,R,Y,E,TA,B,C,D1,D2)
      END IF
C     USE NEXT THREE STATEMENTS ONLY TO RUN T=100 TEST CASE.
C     DO 40 I=1,NR
C     T(I,1)=100.
C     T(I,NZ)=.001
40    CONTINUE
      IF(K.LT.NTP) THEN
      DO 30 I=1,NR
      DO 25 J=1,NZ
25    T(I,J)=W3(I,J)
30    CONTINUE
      END IF
60    CONTINUE
      WRITE(6,101) NR,NZ
101   FORMAT('TESTT - TEMP NR = ',I4,' NZ = ',I4)
      WRITE(6,102)TS,NTP,NTP*TS
102   FORMAT('TIMESTEP = ',E9.3,' NUM STEPS = ',I4,' TIME = ',E9.3)
      WRITE(6,104)
104   FORMAT('TEMPERATURE FOR LAST TIMESTEP')
      DO 80 J=1,NZ
      WRITE(6,100)J,(T(I,J),I=1,NR)
80    CONTINUE
```

```
      WRITE(6,103)
103   FORMAT('TEMPERATURE FOR PRESENT TIMESTEP')
      DO 90 J=1,NZ
      WRITE(6,100) J,(W3(I,J),I=1,NR)
90    CONTINUE
100   FORMAT(I3,11F9.3)
      RETURN
      END
```

# Appendix 5C
## Convective and Radiative Losses from a Freely Burning Cigarette

If the cigarette burns in the open, then the total radiative energy output at time t is

$$\chi_r(t)\dot{m}(t)H_c = 2\pi R \int_0^L \phi_r(x,t)dx \qquad (5C\text{-}1)$$

where $\phi_r$ is given by Eq. (5-28). (This neglects radiation from the ends which is unimportant except at the beginning (t = 0)); similarly for convection,

$$\chi_c(t)\dot{m}(t)H_c = 2\pi R \int_0^L \phi_c(x,t)dx \qquad (5C\text{-}2)$$

where $\phi_c$ is given by Eq. (5-29). Let us estimate $\chi_c$. In order to find the convective cooling flux $\phi_c$, the heat transfer coefficient h is needed. The Nusselt number for the heat transfer by natural convection from a uniform-temperature, long horizontal cylinder in air is (Ref. [5-9], p.275)

$$Nu = 0.53\ Ra^{0.25} \qquad (5C\text{-}3)$$

when the Rayleigh number is in the range $10^4$–$10^9$ (here Ra $\simeq 2.8 \times 10^4$). Hence the heat transfer coefficient for an infinite cylinder of radius R at uniform temperature T is

$$h \simeq 3.43 \times 10^{-4} \left[\frac{T - T_0}{R}\right]^{0.25} \text{W/cm}^2\ ^\circ\text{C} \qquad (5C\text{-}4)$$

with R in cm. [See Muramatsu [5-4], Eq. (8-19)]. It is assumed that the same expression will hold for the cigarette (even though the temperature is not constant and is distributed over a narrow band, rather than a uniform temperature over an infinite band).

The simplest way to evaluate the integral in Eq. (5C-2) is to use the mean-value theorem:

$$\int_0^L \phi_c dx = \bar{h} \int_0^L \Delta T(x)dx \qquad (5C\text{-}5)$$

If the temperature distribution were Gaussian, with standard deviations, i.e.,

$$T(x) - T_a \equiv \Delta T(x) = \Delta T_p \exp-(x\text{-}x_o)^2/s^2, \qquad (5C\text{-}6)$$

then the integral would be

$$\int_0^L \ldots \simeq \int_{-\infty}^{\infty} \Delta T(x)dx = s\sqrt{\pi}\ \Delta T_p \qquad (5C\text{-}7)$$

The integral can also be expressed in terms of the half-width w (the total width at half the peak value, which is easily measured).

$$\int \Delta T dx = \frac{\bar{w}}{2}\sqrt{\frac{\pi}{\ell n 2}}\ \Delta T_p = 1.0645\ \bar{w}\ \Delta T_p \qquad (5C\text{-}8)$$

If the distribution is asymmetric but still Gaussian on each side of the peak, with different values for the standard deviations on each side, then Eq. (5C-8) still holds.

The temperature distribution in Figure 5-4 is not symmetric, but it *is* (roughly) Gaussian on each side. The halfwidth is w $\simeq$ 0.96 cm; and assume that the actual peak temperature is 80° lower than measured, as suggested earlier: $T_p \simeq 555°C$. Since $T_a = 27°C$, Eq. (5C-8) would yield 540 cm-deg for the integral. The Gaussian approximation cannot be very good, however: a numerical integration of the area under the curve in Figure 5-4 yields

$$\int \Delta T_{exp} dx = 763 \pm 14 \text{ cm-deg} \qquad (5C\text{-}9)$$

We assume that the real curve is geometrically similar to the one shown, but scaled down, with a reduced peak of $T_p$. That is,

$$\Delta T(x)_{real} = \left[\frac{T_p - T_a}{635 - T_a}\right] \Delta T(x)_{exp} \qquad (5C\text{-}10)$$

Then with $T_p = 555°C$, the integral falls to 663 ± 13 cm deg. Thus the Gaussian approximation to the integrated flux underestimates the result by 18%. Nevertheless, as will be seen shortly, the Gaussian approximation is useful. The value 663 cm-deg holds for the cigarette on the substrate; for the free-burning cigarette, the value will be different. We will come back to this.

Next, we need to find h in Eq. (5C-5). From Eq. (5C-4), this is h(T), and the appropriate average $\bar{T}$ is required. If $\bar{T}$ is defined in the usual way, the result depends on the interval over which T is averaged. One way to avoid this difficulty is to note that if Eq. (5C-6) held, then

$$[\Delta T(x)]^{5/4} = (\Delta T_p)^{5/4} \exp - (x - x_o)^2/0.8s^2 \qquad (5C\text{-}11)$$

and therefore

$$\int [\Delta T(x)]^{5/4}\, dx = \sqrt{\pi}\, (\Delta T_p)^{5/4}\, s\sqrt{0.8} \qquad (5C\text{-}12)$$

The Gaussian approximation to the integral has been shown above to be inaccurate. However, a large part of that error can be removed by expressing $s\Delta T_p$ in Eq. (5C-12) in terms of the actual integral, *via* Eq. (5C-7). That is,

$$\int [\Delta T(x)]^{5/4}\, dx = (\Delta T_p)^{1/4} \sqrt{0.8} \int \Delta T(x) dx \qquad (5C\text{-}13)$$

Then the *experimental value* can be used for the last integral. This method of estimating $\int \phi_c(x)dx$ in effect yields $\Delta \bar{T} = 0.64\Delta T_p$. With $T_p = 555°C$, $\Delta T_p = 528°C$ and therefore $\Delta \bar{T} \simeq 338°C$, so that Eq. (5C-4) yields[8] $h \simeq 19.3 \times 10^{-4}$ W/cm² deg.

With the (corrected) value of $\int \Delta T(x)dx$, the integral (5C-5) becomes

$$\int \phi_c(x)dx = 663\ (19.3 \times 10^{-4}) = 1.28 \text{ W/cm},$$

and therefore

$$\dot{E}_c = 2\pi R \int \phi_c(x)dx = 2.69 \text{ watts}$$

while on the substrate. In the *air*, the coal is shorter, and this must be reduced. The reduction is by the factor $\ell_c^o/\ell_c$, where $\ell_c^o$ is the coal length in free air (neglecting any change in surface temperature). Again, we will soon return to this. Now

$$\dot{E}_c = \chi_c\ \dot{m}\ H_c$$

Measurements of cigarette 105, smoldering on a substrate, made at the CFR, gave $v = 0.668$ cm/min

and $\qquad \rho = 0.16 \text{ g/cm}^3\ (\pm 3\%)$[9]

Therefore

$$\dot{m} = \pi R^2 \rho v = 37.5 \pm 1.1 \text{ mg/min}$$
$$= 6.25(19) \times 10^{-4} \text{ g/sec},$$

Thus $\qquad \dot{E}_{total} \simeq 6.25 \times 10^{-4}\ (6010) = 3.75$ watts.

This is while smoldering on a flat substrate, however. Experiments (Section 4) have shown that being on the substrate slows down the burning rate by about 17%, on the average. Therefore away from the substrate, we expect

$$\dot{E}^o_{tot} \simeq 3.75/0.83 = 4.52 \text{ W},$$

and thus

$$\chi_c = 2.69/4.52 = 0.595$$

Next, $\chi_r$ is obtained. Using the approximation (5C-7),

$$\int [T^4(x) - T_a^4]dx = \sqrt{\pi}\, as \times \left[\frac{a^3}{2} + \frac{4\sqrt{3}}{3} a^2 T_a + 3\sqrt{2}\, aT_a^2 + 4T_a^3\right] \qquad (5C\text{-}14)$$

where $a \equiv \Delta T_p$.

The factor in front of the bracket is just $\int \Delta T(x)dx$, as is evident from Eq. (5C-7). This has already been found to be, after adjustment, 663 cm-deg. Also, $T_a = 27°C = 300$ K and $a = 528°C$. Then

$$\dot{E}_r = 2\pi R\, \varepsilon_c \sigma \int [T(x)^4 - T_a^4]dx = 3.32 \text{ W},$$

and therefore $\chi_r = 0.734$. Adding the value of $\chi_c$ to it, the result is

$$\chi_r + \chi_c \simeq 1.329$$

Clearly, this sum cannot be greater than 1. Before attempting to rationalize this result, let us determine $\chi_s$ – i.e., the fraction of heat left in the solid:

$$E_s = \int C_p\, \rho\, \Delta T\, dV$$

From Figure 5-2, we estimate that

$$\int \Delta T\, dV = 171.5 \text{ cm}^3 \text{ deg}.$$

About ⅔ of the volume involved at any moment is in ash, $\rho_A \simeq 0.13\ \rho_p$, and ⅓ in char, $\rho_C \simeq 0.34\ \rho_p$. Then with $C_p \simeq 1$ J/gm°C and $\rho_p = 0.16$, we find

$$E_s = (171.5)(1)[⅔(0.13) + ⅓(0.34)]0.16 = 5.5 \text{ Joules}.$$

Finally, $\dot{E}_s = E_s/\tau$,

where $\tau$ is the time required to burn the entire cigarette. At the velocity $v = 0.668$ cm/min., and with a cigarette length $L \simeq 7$ cm, $\tau = 10.5$ min = 630 sec. on the substrate, or 630 (0.83) = 523 sec. in free space.

Thus $\qquad \dot{E}_s \simeq 0.0105$ W,

$$\chi_s \simeq \frac{0.0105}{4.52} = 0.0023$$

[8] *This cigarette has $2\pi R = 2.1$ cm.*

[9] *Note that Muramatsu's cigarette has $\rho_p \simeq 0.259$ g/cm³*

Thus we require $\chi_r + \chi_c \simeq 0.9977$, negligibly different from 1.00. It was found above that assuming $T_p = 555°C$, the sum is 1.33, which is outside the bounds of experimental error. It was seen in Section 4 that the length of the coal is smaller in the open then on the substrate. Suppose the overestimates of energy loss are attributable entirely to this factor. Then the width of the (longitudinal) distribution must decrease from 663 cm-deg to (663)(0.9977/1.329) = 497 cm-deg in order to get the correct energy loss rates. This 25% decline in length is rather larger than any of the experimentally measured declines [see Figure (4-11b)]. Moreover, since the surface temperatures will be higher away from the substrate, the decline in length would have to be still greater. The source of this discrepancy is not clear. However, this reduced length yields (in open air)

$$\dot{E}_c^o = 2.02 \text{ W} \quad \text{and} \quad \dot{E}_r^o = 2.49 \text{ W},$$

or

$$\chi_c = 0.447 \quad \text{and} \quad \chi_r = 0.551$$

Thus, the energy leaves the cigarette by convection and radiation in comparable amounts.

# Appendix 5D
## Derivation of the Transverse Conductive Flux Distribution

Consider the transverse flux distributions; first, that for the conductive flux. This will be found in a simple analytic approximation. The simplest approximation is to treat the cigarette as if it were an infinitely long cylinder at uniform temperature. This further suggests treating it as a "buried cable" (buried in air, which is assumed to be entirely quiescent — i.e., all boundary layer — between the cigarette and the substrate). Since the rest of the air is *not* static, this treatment can only be a crude approximation, of course.[10] The situation is as shown in Figure 5-19. The "cable" is of radius $r_o$. Its center is the distance N from the surface, which is at the uniform temperature $T_s$. The cable can be replaced by an equivalent line source, a distance $a < N$ from the surface. In the steady state, the surface temperature of the cable can also be specified to be $T_o$. The line-source approximation for the transient case is done in Carslaw and Jaeger [5-6], p. 261. For the line source, they take the heat liberated to be at the (possibly variable) rate

$$\rho C\phi(t) \equiv Q' \qquad \text{(5D-1)}$$

per unit length. This source is in a static material at an initially uniform temperature $T_a$; the heat is turned on at $t=0$. If $\phi(t) = \text{const} = q$, then the temperature in the surrounding material at any point P a distance r from the source is given by

$$T(r,t) = T_a + \frac{q}{4\pi x} E_1\left(\frac{r^2}{4\alpha t}\right) \qquad \text{(5D-2)}$$

at time t, where $\alpha$ is the thermal diffusivity and $E_1$ is the first exponential integral. From Eq. (5D-1),

$$\frac{q}{\alpha} = \frac{Q'}{k} \qquad \text{(5D-3)}$$

By using the image method, we find that for the case where we have the source in a semi-infinite space, with the surface kept at $T_a$,

[10] *An alternative analysis was also carried out, but was no better.*

$$T(r,t) = T_a + \frac{Q'}{4\pi k}\left[E_1\left(\frac{r^2}{4\alpha t}\right) - E_1\left(\frac{r_1^2}{4\alpha t}\right)\right] \qquad \text{(5D-4)}$$

$r_1$ is the distance to the sink (the image line). In the limit $t \to \infty$, Eq. (5D-4) yields the steady-state solution,

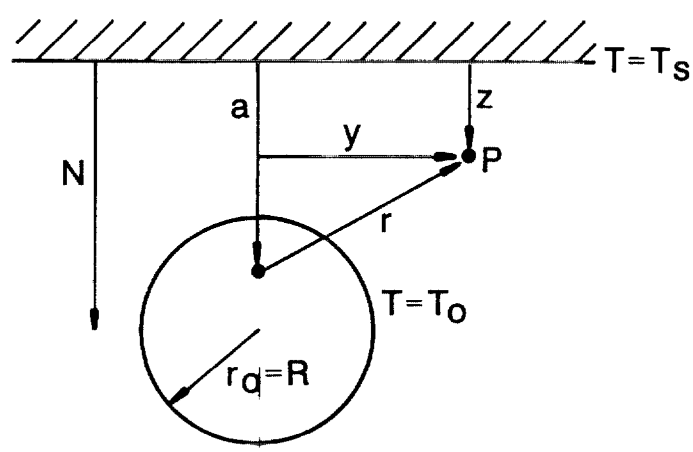
$$T(r) = T_a + \frac{Q'}{4\pi k} \ell n \left[\frac{y^2 + (a+z)^2}{y^2 + (a-z)^2}\right] \qquad \text{(5D-5)}$$

where z is the (normal) distance from the point to the plane, y the orthogonal distance, as shown in Figure 5-19. The isotherms are cylinders, and the "cable" surface is one of them.

The transient heat flux towards the surface is easily found from Eq. (5D-4); it is

$$\phi(x,z,t) = k\frac{\partial T}{\partial z}$$

**Figure 5-19. Cross Section of Buried Cable, with Various Distances and Temperatures Indicated.** **The Distance N-R Between the "Cable" Surface and the Shaded Substrate Above is Grossly Exaggerated for the Purpose of Clarity.**



$$= \frac{Q'}{2\pi}\left[(a+z)\frac{exp(-r_1^2/4\alpha t)}{r_1^2}+(a-z)\frac{exp(-r^2/4\alpha t)}{r^2}\right] \quad (5D\text{-}6)$$

Note that with this line-source approximation, the cigarette surface is an imaginary surface around the source, and therefore the initial cigarette temperature, in this approximation, is $T_a$; it only rises because of conductive heating by the line source.

The steady-state flux towards the surface can be obtained either by taking the $t \rightarrow \infty$ limit of Eq. (5D-6), or by differentiating Eq. (5D-5) with respect to z. Then the flux at the boundary – i.e., the surface z = 0 – is

$$\dot{q}''(y,0) = \frac{Q'}{\pi}\frac{a}{a^2+y^2} = \dot{q}''(0,0)\frac{a^2}{a^2+y^2} \quad (5D\text{-}7)$$

Since this is a steady-state result, it is important that we know how close to the steady state the system really is. One can easily estimate how long it would take to achieve steady state, if the air were everywhere static: it is (roughly) the time it will take to heat up the air space between the source and the boundary to the mean temperature between them (about 280°C). The volume of air between the cigarette and the substrate is $(2 - \pi/2)r_o^2$ per unit length. Taking reasonable values for the cigarette energy output, air density, and specific heat, this time is about 5 milliseconds.

When the cigarette is first dropped on the substrate, the principal heat flux from it to the substrate is radiative only, and therefore the mean heating flux is about 2 W/cm². Therefore, for a typical substrate, the surface temperature will only rise by 15-20°C in the 5 ms calculated above. In that time, the air has just about reached its steady value for that substrate temperature. Since the substrate response is relatively slow, the steady-state solution for the "buried cable" can be used to obtain a fair approximation to the initial conduction flux. Indeed, the dependence given by Eq. (5D-7) agrees (semi-quantitatively) with measurements (Section 4).

Thus, the form of the desired transverse dependence has been found. One can either use the knowledge of the initial conduction flux along CL to get the initial solution everywhere (*via* Eq. (5D-7)), or the fact that the cigarette surface temperature is known, using Eq. (5D-5). In either case, the parameter a is needed in order to get an explicit answer; in order to find it, the transcendental equation

$$C_o = 1 + \frac{8k(T_c - T_a)\sqrt{C_o}}{\dot{q}''(0,0)\, r_o \ln C_o} \quad (5D\text{-}8)$$

must be solved for $C_o$; then

$$a = \frac{4\,k(T_c - T_a)}{\dot{q}''(0,0)\ln C_o} \quad (5D\text{-}9)$$

An explicit estimate for a can now be made. The cigarette surface temperature is depressed by the presence of the cold substrate (or cold gauge); suppose that the peak temperature drops to about 550°C; at that point, the measured (peak) flux is about 5.6 W/cm². With a measured emissivity of $\varepsilon_c \simeq 0.73$, a surface temperature of 550°C radiates at the (net) rate of 1.87 W/cm², so that the conduction flux to the surface must be 3.73 W/cm². With this flux, if $r_o$ = 0.4 cm, we find (from Eq. (5D-9)) that a = 0.23 cm, and an effective minimum distance $\delta \simeq 0.6$ mm between the cigarette and the substrate along CL, is inferred. With this value of a, the instantaneous (but calculated as if this were a steady state!) conduction flux at the distance $y = r_o$ would be about 24% of the value at the centerline (y=0). If $\delta$ is given, then so are a and $C_o$; hence Eq. (5D-9) relates $T_c$ and the peak conduction flux, $\dot{q}''(0,0)$. A more accurate analysis is necessary in order to obtain more realistic results.

In the remainder of this appendix, the total rate of conduction to the substrate is estimated. First, assume the results of the above analysis: assuming that Eq. (5D-7) gives the transverse dependence for all x, the total conductive energy flow $\dot{E}_{cd}$ is

$$\dot{E}_{cd} = \int\int \dot{q}''(x,y)dxdy$$

$$\int = \int dx\ \dot{q}''(x,0)\int_{-\infty}^{\infty} dy\frac{a^2}{a^2+y^2} = a\pi\int \dot{q}''(x,0)dx$$

It was found that for the *total* flux, $\int\phi_t(x)dx \simeq 6.07 \pm 1.0$ W/cm; hence for the conduction flux,

$$\int \dot{q}''(x,0)dx \simeq \frac{3.73}{5.6}(6.07 \pm 1) = 4.05\ ^{+.73}_{-.60}\ \text{W/cm};$$

With a = 0.226, therefore,

$$\dot{E}_{cd} = a\pi(4.05 \pm \ldots) = 2.87\ ^{+.54}_{-.42}\ \text{watts.}$$

(However, see Eq. (5D-13)). This can be approached another way: Experimental measurements have shown that the flux from a cigarette can be fitted with a distribution of the form (5-5). This agrees with Eq. (5D-7), to lowest order in y². The total energy output from this distribution is

$$\dot{E} = \int\int \phi(x,y)dxdy = \pi\sigma_x\sigma_y\phi_m \quad (5D\text{-}11)$$

The average central peak has been measured to be about 5.6 W/cm², of which about 1.9 W/cm² is radiation; therefore $\phi_m \simeq 3.7$ W/cm². Moreover, $\sigma_x \simeq 0.61$ to 0.7 cm, $\sigma_y \simeq 0.32$ to 0.36 cm. A Gaussian distribution would then yield

$$\int\phi(x,0)dx = \phi(0,0)\sqrt{\pi}(\sigma_x) \simeq 5.6\sqrt{\pi}\,\sigma_x$$

Then $\sigma_x = 0.62 \pm 0.1$ cm yields $6.15 \pm 1.0$ W/cm for the integral. This agrees very well with the measured 6.07 W/cm, and suggests that Eq. (5D-11) will also give an accurate result; with $\sigma_y = 0.36$ cm, it yields

$$\dot{E}_{cd}(0) = 2.58 \text{ watts},$$

in close agreement with the earlier estimate. This, then, purports to be the total initial convective flow to the substrate from the cigarette.

There are two effects which must modify these calculations of $\dot{E}_c(0)$: First, a convective flow is set up around the cigarette, as shown by the streamlines in Figure 5-20 (labelled by arrowheads). The shaded region under the cigarette is (relatively) quiescent and is principally involved in conduction; conduction through the convective region is much smaller. Hence Eq. (5D-7) is to be integrated only for the region $-\xi < y < \xi$. That is, the absorbed convective energy is

$$\dot{E}_{cd} \simeq 2L \int_0^{\xi} \dot{q}''(y)dy =$$

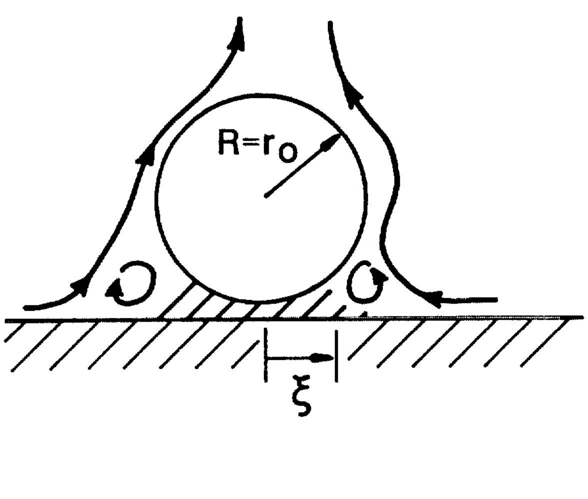
$$= \frac{2aLQ'}{\pi} \int_0^{\xi} \frac{dy}{a^2 + y^2} = 2La\, \dot{q}''(0,0) \tan^{-1} \frac{\xi}{a} \qquad \text{(5D-12)}$$

(where Eq. (5D-7) was used in the form $Q' = \pi a \dot{q}''(0,0)$). More properly, integrating along the CL,

$$\dot{E}_{cd}(0) = 2a \tan^{-1} \frac{\xi}{a} \int_0^{L} q''(x,0)dx \qquad \text{(5D-13)}$$

This is the generalization of Eq. (5D-10); for $\xi < \infty$, therefore, the convective loss rate will be smaller than what was calculated above, from this effect alone.

**Figure 5-20. Cross Section of Cigarette on Substrate. Heat Conduction from the Cigarette Occurs Mainly Within the Shaded Region. The Curves with Arrows Indicate the Air Streamlines.**




The second effect relates to radiation, and works in the opposite direction: the radiative component falls as $T^4$, whereas the conductive component falls linearly with T. Thus the ratio of $\phi_r$ to $\phi_c$ is highest at the peak: $1.87/3.73 \simeq 0.5$, and falls outside the peak. It is not difficult to show that the ratio of the standard deviations of the two distributions (assuming each is Gaussian) is about 1.48. It follows that $\int\phi_r dx = 1.52$ and $\int\phi_c dx = 4.55$, so that the mean ratio is 0.33, rather than 0.5. Thus, while the *total* distribution has $\sigma_x = 0.61$ cm, the radiative and conductive distributions separately have $\sigma_r = 0.45$ and $\sigma_c \simeq 0.67$ cm. Thus the expression (5D-13) must be increased by the factor $0.67/0.61 \simeq 1.1$, and the integral in this equation must be increased from 4.05 to 4.45; then Eq. (5D-13) yields

$$\dot{E}_{cd}(0) = 8.90\, a \tan^{-1} \frac{\xi}{a}$$

For $\xi = r_o = 0.4$ cm, $\dot{E}_c(0) = 2.13$ w. This corresponds to $\sigma_y = 0.30$ cm, rather than 0.36 cm. Thus the overall effect is to reduce the conductive loss.

At later times, the conductive flux falls: If the mean surface temperature of the substrate at time t is $T_s(t)$, then at later times

$$\dot{E}_{cd}(t) \simeq \dot{E}_{cd}(0) \left[ \frac{\bar{T}_c - T_s(t)}{\bar{T}_c - T_a} \right] \qquad \text{(5D-14)}$$

where $\bar{T}_c$ is the mean cigarette surface temperature. Assuming the substrate temperature profile resembles that of the fluxes, it is easy to see (since the conduction loss is linear in T) that we only need the peaks of the temperatures to find the total conduction flux. Hence Eq. (5D-14) may be replaced by

$$\dot{E}_{cd}(t) \simeq \dot{E}_{cd}(0) \left[ \frac{T_p - T_s(t)}{T_p - T_a} \right] \qquad \text{(5D-14)}$$

where $T_p$ is the peak cigarette surface temperature. This concludes the discussion of convective heat transfer to the substrate.

## Section 6

# Evaluation of Test Methods for Cigarette Ignition Propensity

## Contents for Section 6



## List of Tables and Figures

# Introduction

A key task commissioned by the Technical Study Group was the development of a suitable measurement for cigarette ignition propensity. Such a test method would serve as a tool in research and development, for quality control in manufacturing, and as a test for regulatory efforts. The initial approach to this task was to evaluate test methods suggested in the literature. Since no fully satisfactory method was found, a few new concepts were investigated. This work could not be completed in the time period allowed, but insight into the problems and chances of success of various candidate test concepts was gained. Consequently, this section is a progress report, documenting the development efforts as an aid to future research. Various candidate methods are evaluated in Sections 6.1 to 6.4; the most promising concept is described in more detail under 6.5.

This work could not be started until cigarettes with varying degrees of ignition propensity, including very low levels, had been identified. Section 3 shows that the relatively low ignition propensity of such cigarettes found in the primary evaluation (consisting of testing cigarettes on three substrates and noting the total number of ignitions) was validated by extensive further evaluations. These additional evaluations were conducted on numerous substrates, ranging in cigarette ignition resistance from intermediate to very low. This range was due to variations in fabric/padding (and in some cases, welt-cord) variations and configurations, as well as fabric contamination; it included substrates with near worst case cigarette ignition resistance. It thus seems reasonable to assume that the observed differences in cigarette ignition propensity during screening on these substrates would prevail in most real life scenarios in which a cigarette falls on soft furnishings, and that the primary evaluation ignition results provided a credible basis for test development. The scope of this project did not include the extension of this work to wildland substrates, such as forest or grassland covers.

With the present state of the art, evaluation of the ignition propensity of a given cigarette would have to be carried out on a variety of substrates with graduated cigarette ignition resistance, including very low values, to assure testing under near worst case conditions. (This is essentially the methodology of the above mentioned "primary evaluation" and validation.) The substrates should consist of commercial fabrics and cotton batting or polyurethane foam padding, in a variety of configurations. The problem with this approach has been the limited degree of reproducibility of commercial materials; strict quality control at every production step may overcome this deficiency. A general outline suggesting means to minimize this problem is given in Section 6.5. Such a test procedure would resemble the approval testing of new drugs and cosmetics, where no standard protocols in the strict sense exist but general guidelines have to be followed.

Before much experimental work with the ignition propensity of cigarettes had been performed, it was assumed that a cigarette with a low burn rate in air would have low ignition propensity [6-1]. Well-developed methods for measuring burn rate of cigarettes in air exist [e.g., 6-2]; however, as discussed in Section 3, these burn rates do not appear predictive of ignition propensity. In fact, a good overall correlation between mass burning rate measured in air by one of the cigarette company laboratories and ignition propensity was found for the first series of experimental cigarettes (no data were furnished for the second series). However, at the low ignition propensity range, the range of interest, the mass burn rate in air did not predict ignition propensity accurately. Also, the correlation was improved when calculated separately for the Burley and flue cured cigarettes. It would have to be established whether the relation ship between mass burning rate and ignition propensity is tobacco type dependent; the ignition propensity results did not show such a dependency in the present experiments. Temperatures of cigarettes burning in air have been measured in our and other laboratories (Section 4) [e.g., 6-3,4]. They require rather sophisticated equipment, and their ability to predict ignition propensity is questionable.

The reason that these and other measurements of cigarette properties in air do not seem to be sufficiently predictive of their ignition propensity on substrates may be the strong interaction between cigarette and substrate [6-5,6]. More specifically, there are changes in cigarette burn rate and heat output which depend on the nature of the substrate in contact with the cigarette. The effects of the substrate on temperature/time relationships inside a cigarette were discussed in detail in [6-5] and are briefly reviewed here. The temperature measured in the center of a cigarette was highest and the time/temperature peak sharpest when the cigarette burned in air. The peak was lower and broader when the cigarette was placed on a substrate on which smoldering occurred in the area near the cigarette but did not spread (no self-sustaining smoldering ignition). The temperature was initially still lower, and for a longer period of time, on a substrate which ignited, i.e., the smolder spread continuously from the cigarette area. After full involvement of the fabric and polyurethane foam, the temperature in the cigarette rose. Similar effects of substrates on cigarette temperature and burn rate are discussed in Section 4 of this report, with the emphasis on the time period prior to self-sustaining ignition of the fabric.

It thus appears that, because of this potential for significant interaction between the burning cigarette and the substrate, any method for the measurement of cigarette ignition propensity should be based on its smoldering behavior on one or several "standard" substrates.

# Methods Suggested in the Literature

Several methods for measuring cigarette ignition propensity were discussed in a recent paper by Norman [6-7]. Differences in ignition propensity had been defined for four experimental cigarettes varying in packing density and circumference by testing them on almost 200 substrates (33 fabrics, 2 paddings, 3 configurations). About a dozen methods to measure the heat output of these cigarettes were considered, and four were explored in greater depth. Two of these selected methods tested the cigarettes in air and two on substrates. The author concluded that the heat output of the experimental cigarettes varied widely when the cigarette burned in air, but that the nature of the substrate became dominant when they were burned on substrates. For the record, the methods explored in some depth by Norman were:

a. The measurement of the surface heat flux/time relationships from cigarettes smoldering in air by means of a heat collector. The resulting plots were analyzed in terms of maximum heat flux, time above certain heat flux values, etc.

b. The measurement of the total heat release from cigarettes suspended in air near a water bath covered with aluminum foil. The rise in water temperature was recorded.

c. The determination of the weight loss rate of various cigarette/substrate systems which smoldered. Since this was found to be mostly substrate dependent, Norman did not consider it promising. Similar conclusions were drawn in our earlier work [6-8].

d. Measurement of the volume of the smolder imprints and the time of burning of smoldering cigarettes on polyurethane blocks. (Without the fabric cover, the polyurethane does not smolder but melts and partially chars when a cigarette is placed on it.) This method seemed promising, and was further pursued in our laboratories, as described below.



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# Weight Loss of Polyurethane Foam

Following the above lead, the weight loss of polyurethane foam exposed to cigarettes varying in ignition propensity was investigated. Most polyurethane foams do not continue smoldering after the cigarettes burn out, but leave a visible imprint. Norman suggested the measurement of the volume of such imprints by filling the imprints with small beads of known packing density and weighing the beads as a measure of the cigarette ignition propensity. We found it more convenient to measure the weight loss per unit length of cigarette. However, we found later that this method lacks in precision. Perhaps the volume measurements would have been more precise, because part of the polyurethane foam does not pyrolize but melts and shrinks back from the cigarette, creating a cavity. It is possible that the cavity sizes correlate better with cigarette ignition propensity than the weight loss which only depends on the amount of pyrolized material. However, in a recent communication to the TSG it was pointed out that polyurethane foams on the market vary widely in cigarette ignition resistance, and that it may be difficult to obtain a standard foam for the purposes of this test [6-9]. This is discussed in greater detail below.

## Procedure

Polyurethane foam (HD 2045, 51 mm (2 in.) thick) was cut into 127 × 203 mm (5 × 8 in.) blocks. The blocks were dried at 100°C for 3 hours and placed in a desiccator over silica gel until ambient temperature was reached (30-60 min.). The blocks were removed from the desiccator and immediately weighed on a balance with 0.01 g resolution. The blocks were placed on recording balances to obtain weight loss curves. Five conditioned cigarettes were sampled from each of the 41 experimental cigarettes, the patented cigarettes and their controls, and the three commercial controls. These were weighed, then lighted and placed on the block such that the cigarette paper seam was not in contact with the foam. After all cigarettes were on the block the weight loss recording program was started. If a cigarette self-extinguished it was removed from the block, lighted again and placed back on the block in the same spot that it had previously occupied. If any, or all, of the five replicate cigarettes repeatedly self-extinguished, it was noted and the partial weight loss value was recorded. After all of the cigarettes on a block had burned to completion, the program was stopped and the weight-loss curve was printed out. The residue from the burned cigarettes was discarded and the blocks were again dried and weighed as previously described. The weight loss of the foam blocks was recorded.

## Comparison of Weight Loss Results and Number of Ignitions

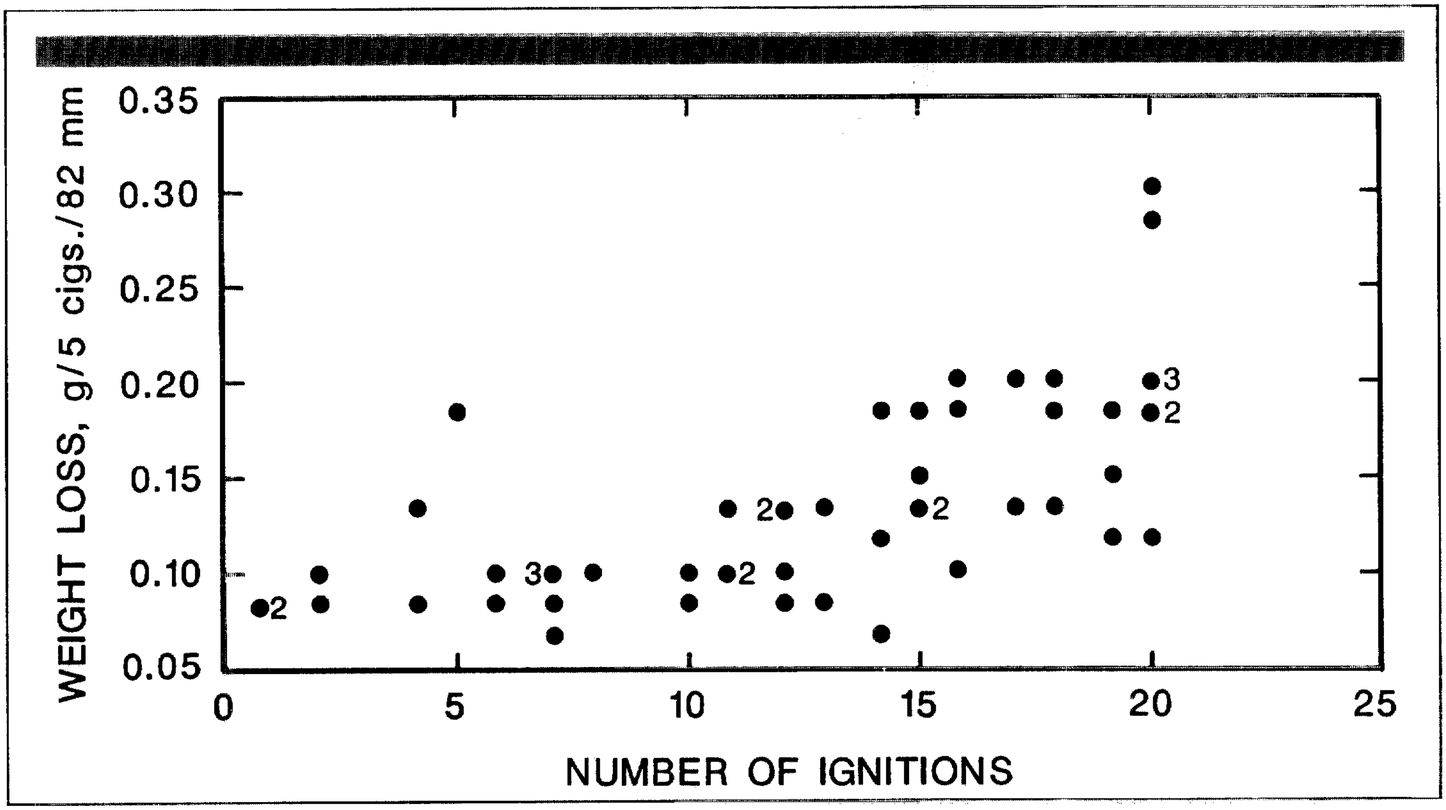
Figure 6-1 shows a comparison of the weight loss values and the corresponding number of ignitions on the substrates obtained in the primary evaluation discussed in Section 3. While a weak correlation exists (correlation coefficient = 0.69), this did not appear an acceptable predictive test for cigarette ignition propensity, at least with the limited sampling used in this comparison. This holds particularly in the range of interest, the low ignition propensity range.

The above results were obtained by use of only one foam block with five cigarettes on it. Table 6-1 shows the results obtained with selected cigarettes when five foam block replicates, each with five cigarettes smoldering, were exposed. Statistical analysis of the results indicates that even with 50 replicates, the correlation coefficient would only be 0.76 [6-10]. Obviously, this evaluation method in its present form shows little promise. However, Norman's original suggestion, to measure the volume of the cigarette imprints, should be tried.

Several possible reasons for this lack of precision come to mind. One was that we were operating at the limits of the balance; furthermore, the polyurethane foam lost some weight during the heating (for conditioning purposes, as described above) after exposure of the cigarettes. This heating would be unnecessary if the foam imprint volume rather than the weight loss were measured. Variability of the foam chemistry or cell configuration was also suspected as a reason for the lack of precision of the results—assuming, of course, that the experimental cigarettes are consistent in their effect on the foam substrate.

It is well known that different production lots of polyurethane foam vary in their response to burning cigarettes.

**Figure 6-1. Relationship of Polyurethane/Cigarette System Weight Loss and Number of Ignitions Obtained in Primary Evaluation**




NOTE: Numbers adjacent to a symbol refer to multiple points at that location

The CPSC has repeatedly returned shipments of the "Standard UFAC" foam because they did not behave like earlier shipments when tested with certain fabrics [6-11]. UFAC suspected that vertical position in a foam bun (production unit of extruded foam roughly 1 m thick) may be a cause for such variable results. However, ignition/non-ignition tests at the UFAC laboratories did not show this difference [6-12]. Close control of foam chemistry and cell configuration in foams over small distances or even among production lots has probably never arisen as a practical problem. Thus an improvement may not be of interest to the foam industry and it may be difficult to find a foam producer who would be prepared to make a more reproducible foam.

It may be possible to characterize the foam by using an electric heating element resembling cigarettes. Such heaters have been tried in connection with attempts to develop a "standard cigarette," with inconclusive results [6-13]. In practice, one could test a set of cigarettes on one side of the foam block, and later apply the heat source to the other. The results could then be expressed as the ratio of the weight loss due to the smoldering cigarettes to the weight loss due to the standard heating source. Alternatively, one could use a commercial cigarette as the standard, assuming, of course, that they are closely controlled in heat output. Time did not permit exploring these approaches.

## Table 6-1. Weight Loss of Polyurethane Blocks Caused by Smoldering Cigarettes Five Blocks with 5 Cigarettes Each

| | | | Foam Weight Loss | | | |
|---|---|---|---|---|---|---|
| Cigarette Number | Circumference (mm) | Total Number Ignitions[a] | Average (g) | Range (g) | Std. (Dev. | Std. Error (%) |
| 106 | 21 | 1 | 0.08 | 0.04-0.12 | 0.03 | 35 |
| 107 | 21 | 11 | 0.10 | 0.08-0.12 | 0.01 | 10 |
| 112 | 21 | 20 | 0.16 | 0.13-0.20 | 0.03 | 19 |
| 130 | 25 | 4 | 0.09 | 0.05-0.12 | 0.03 | 31 |
| 122 | 25 | 7 | 0.09 | 0.06-0.10 | 0.02 | 22 |
| 127 | 25 | 20 | 0 22 | 0.19-0.26 | 0.03 | 14 |
| 201 | 21 | 0 | 0.05 | 0.03-0.07 | 0.01 | 20 |

(a) In primary evaluation

# Cigarettes Burning on an Alpha-Cellulose Substrate

In earlier work, ignition propensity rankings were obtained for six commercial cigarette packings by testing them on a variety of substrates [6-14]. Similar rankings were obtained in tests in which the weight loss rate of cigarettes smoldering on alpha-cellulose paper (used in chromatographic analyses) of the cigarettes was determined. This paper smoldered along with the cigarettes but did not sustain the smolder after the cigarettes burned out. However, when this test was applied to the low ignition propensity cigarettes from the present series, the alpha-cellulose did not smolder and no weight loss occurred. Consequently, no cigarette ranking at the lower end of the ignition propensity scale was possible. However, treatment of the paper with alkali metal ions may decrease its cigarette ignition resistance, allowing its use as a standard material for measuring ignition propensity in the low range. This possibility could not be explored under the present program.

# Cigarettes Smoldering on a Glass Plate

An inert substrate, such as a glass plate, would have the advantage of retaining its response to heat emanating from the cigarette in repeated tests. This could overcome the reproducibility problems of fabric/padding substrates. On the other hand, the thermal characteristics of the glass plate are very different from those of fabric substrates, and may not produce the same effect on the cigarette with respect to heat sink action and oxygen blocking. Our work with glass plates indicated early on that differentiation between commercial and low ignition propensity cigarettes was possible, but for differentiation between intermediate and low ignition propensity cigarettes, the system would have to be heated.

## Methods

A piece of plate glass 1.6 × 152 × 152 mm ($\frac{1}{16}$ × 6 × 6 in.) weighing 137 g and a brass block 25 × 152 × 152 mm (1 × 6 × 6 in.) weighing 5.4 kg were placed on a Thermolyne Type 1900 hot plate with the brass plate directly on the hot plate surface and the glass plate resting on the brass surface. A type K thermocouple was placed at the center of the top of the glass plate and held in place with a 100 g weight. The perimeter of the glass plate was surrounded by a 25 mm (1 in.) thick fiberglass insulation with the glass surface 51 mm (2 in.) below the top of the fiberglass frame. The thermocouple was connected to a Doric Trendicator 415A meter. The hot plate was placed in series with a Powerstat Variable Autotransformer. The temperature control on the hot plate was set to maximum and the temperature was regulated with the Autotransformer. This system controlled the measured temperature within a range of 5°C.

The low ignition propensity cigarettes BELN-21, No. 106, FELN-21, No. 114, and 201, the intermediate ignition propensity cigarette FELN-25, No. 129, and the commercial cigarette No. 6 were selected to provide a wide range of ignition propensities. The cigarettes were lit and allowed to burn in air for one minute. The entire group of cigarettes was then placed on the glass surface. The temperature was increased slowly and observations for each group of cigarettes at the increasing temperatures were reported with respect to which cigarettes continued to smolder on the heated surface.

In a few experiments, the glass plate was replaced with a piece of heavy duty aluminum foil. At ambient temperature the high ignition propensity cigarette failed to burn to completion. Because of a limited time for experiments, it was decided not to pursue the experiments on aluminum foil at increased temperatures, because the thermal responsivity of aluminum is even more different from that of fabric than that of glass.

## Results

At ambient conditions, the commercial cigarette smoldered along its entire length and the others self-extinguished. The temperature of the glass plate was then raised as described above. Not until the temperature reached 86.5°C did any of the cigarettes except the commercial No. 6 smolder to completion. Between a temperature of 86 and 97°C, replicates of the other cigarettes smoldered in a random fashion, i.e., some smoldered to completion, others partially. No difference between the low and moderate cigarettes was evident.

One could hope that very tight temperature control of the experimental environment could lead to better differentiation between cigarettes. A closely controlled oven comes to mind. All the cigarettes exposed at one time on the glass plate should be the same kind, to avoid simultaneous exposure of cigarettes with different response to heat. Rather than relying on visual inspection of smoldering, cigarette weight loss could then be determined. This would permit one to account for cigarettes which smoldered only partially. Finally, sintered glass plates should be considered since their thermal responsivity would be closer to that of fabrics than that of ordinary glass. However, reproducibility of sintered glass surfaces and feasibility of removal of condensation products would have to be established.

# Tentative Test Method Using Fabrics and Padding Materials

## General Considerations

In previous work, a series of substrates varying in cigarette ignition resistance was obtained, often by trial and error [e.g., 6-14,15,16] and cigarette ignition or non-ignition observed. The ignition propensity of various cigarettes could then be determined by the number of substrates ignited. This worked reasonably well for any set of fabric/padding combination; but as soon as a new roll of supposedly identical fabric or lot of padding material was used, reproducibility problems often arose [e.g., 6-8,17]. One could expect problems even within a lot or shipment of these materials, because they are generally poorly controlled. Even different shipments of the UFAC and California Bureau of Home Furnishings standard fabrics and UFAC standard foam have been found to vary in ignition propensity [6-11,17]. This section explores means to minimize the effects of such variability in substrate characteristics.

Among the reasons for the lack of reproducibility of substrate materials is the fact that upholstery fabrics are produced primarily with control of appearance in mind. The best controlled property may be dye shade and not even that is always the same, as one can sometimes observe by comparing chairs and sofas sold in sets. We also have found backcoating thickness to occasionally vary over a short length of fabrics. In one case, we found differences in fiber content (100 percent cotton vs. polyester/cotton yarns) in supposedly identical fabrics. Similarly, yarn size and twist, number of yarns per unit area, crimp, pile height, etc, can vary, and the effect of these and other construction variables on cigarette ignition resistance has never been systematically investigated. However, while one can expect poor quality control of furniture cover fabrics, certain industrial fabrics, such as cotton ducks, are produced to fairly close construction specifications. One such fabric was used in the study of fabric contamination discussed above; it only smoldered when contaminated with alkali metal ions.

To prepare substrates for cigarette ignition propensity testing one would have to control the smolder promoter (e.g., alkali metal ions) or inhibitor content of fabrics. Controlling such concentrations in fabric manufacture may go a long way towards obtaining reproducible standard fabrics as well as reducing cigarette initiated fires. One could choose industrial fabrics produced in large volumes to certain specifications such as cotton ducks, very thoroughly desize and scour them, and then treat them with varying concentrations of alkali metal ions to obtain fabrics with systematically varying cigarette ignition resistance. However, very accurate control of the concentration of any finishing agent is difficult even in closely controlled laboratory experiments. Full exploration of the effect of normally occurring process variations affecting alkali metal concentrations on cigarette ignition resistance of fabrics could not be carried out under the present program.

Ihrig *et al.* [6-15] identified fabric density and weight per unit area as parameters which affect cigarette ignition resistance. They also developed a method of defining another such parameter, the "smoldering proclivity" by observing the smoldering characteristics of yarns taken from the fabrics. Smoldering was initiated by means of an electric heater, at the bottom end of vertical yarns taken from the fabric, and the progress of the smolder observed. This correlated well with the sodium and potassium ion content of the fabrics. These methods could be used to check the quality control of fabrics used for cigarette testing.

The choice of a "standard" padding material could proceed along similar lines. Cotton batting is innately very variable, and polyurethane foam chemistry and cell distribution are not adequately controlled, as shown in the above described weight loss experiments which were conducted without fabric. It may be possible to use multiple layers of one well defined fabric as the substrate, obviating the need for a separate padding.

## Outline of Suggested Tentative Test Method

To be able to measure the ignition propensity of cigarettes by testing over a period of time, the following is suggested:

a. Acquisition of several hundred yards of a very well desized and scoured industrial, 100 percent cotton duck fabric or similar fabric and a single, optimally controlled batch of polyurethane foam. In mockup form, this fabric/foam combination should not ignite with commercial cigarettes. (If pilot experiments show that multiple layers of one fabric can be used as standard substrates, the foam would not be needed.)

b. Treatment of the fabric with various concentrations of compounds containing alkali metal ions or other smolder promoters. At the lowest level, it should ignite with the commercial cigarettes. At the highest level, it should ignite with the lowest ignition propensity experimental cigarettes available. Intermediate levels should ignite with the commercial cigarettes but not the lowest ignition propensity cigarettes. If cigarettes with even lower cigarette ignition propensity are developed, even higher smolder-promoter concentrations would have to be applied. (It remains, however, to be determined that cigarette ignition resistance decreases infinitely with increasing alkali metal concentrations. It may be necessary to change the base fabric to one with lower cigarette ignition resistance or use multiple layers of one fabric to vary substrate ignition resistance.)

c. The fabric pieces should be sampled at frequent intervals along their length. The sample specimens should be characterized by the standard textile measurements of their weight, density, yarn size and twist, number of yarns per unit length, and air permeability, as well as by determination of the smolder-promoter concentration and by the above mentioned yarn smoldering test [6-15]. Similarly, thermogravimetric analysis and perhaps other characterization tests of foam specimens should be conducted. If large variations of these properties are encountered, fabric areas and polyurethane foam sheets ought to be arranged into groups of similar properties, and only the largest of those should be used for cigarette evaluations. Similar procedures are used in cigarette testing, where the weight distribution of a large sample is determined and only cigarettes in the median weight group are tested [6-18]. Cigarette comparisons should then be carried out on fabric and foam specimens of similar ignition resistance.

d. As an alternative to the alkali metal treatments, one could obtain yardage of fabrics with innately varying cigarette ignition resistance, and use them in the manner described in a. The production of such fabrics should be strictly quality controlled at each step, to assure piece-to-piece reproducibility.

e. Measurement of relative char damage by cigarettes varying in ignition propensity on substrates which smolder along with the cigarettes but do not sustain smoldering when the cigarettes burn out may supplement the above ignition/non-ignition evaluations. Weight loss measurements along these lines have shown poor reproducibility in previous work [6-8], but this may not be the case if the substrates (and cigarettes) were more closely controlled.

f. The sensitivity of ignition propensity measurements to fabric smolder promoter concentration and variations in foam thermogravimetric results should be investigated. Similarly, the effect of ageing on these properties should be established.

The smoldering propensity of experimental cigarettes could then be investigated on such substrates. During such tests, relative humidity and temperature in the test room, and air velocity and direction with respect to the smoldering front movement of the cigarette in the immediate area of the test should be closely controlled. As more experience is obtained with this method, pass-fail criteria could be established. These could then be checked against the results obtained on laboratory mockups of low cigarette ignition resistance fabric/padding combinations, as well as on discarded, soiled furniture. In many cases, both flat surface and crevice tests should be undertaken. (Work described in Section 3 shows that for the low ignition propensity, experimental cigarettes, crevices may be equally cigarette ignition resistant as flat cushions, while for commercial cigarettes, crevices always had lower cigarette ignition resistance [6-19].) Consequently, tests for measurement of the ignition propensity should be conducted in both configurations.

# I

# Summary


A number of candidate test methods for the propensity of cigarettes to ignite upholstered furniture have been evaluated. It appears that such a test method would have to consist of a cigarette on a substrate rather than with the cigarette in air, because of the substrate-cigarette interaction (heat sink effect and blocking of oxygen).

Two types of substrates were considered: (1) upholstered type combinations of fabric and padding, and (2) more permanent, re-usable substrates such as glass plates. Upholstery materials present a problem in their lack of reproducibility. Procedures to minimize this are discussed; they involve close cooperation with the material producers.

A number of test methods which would not have to rely on use of fabrics and padding have been investigated, albeit not in depth because of the short period available for this work. None of these could be recommended without further evaluation. These include measurement of the weight loss or imprint volume of polyurethane foam blocks on which smoldering cigarettes have been placed; determination of full length burning or self-extinguishment of cigarettes placed on a glass or pyrex plate held at various temperatures; and perhaps some of the measurements discussed in Section 4.

This work has not produced a test method. It may have narrowed the field from a large number of potential candidates, and pointed towards the next steps to be taken in further development of the more promising approaches.

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# Section 7

## Conclusions

# Conclusions

The following are the principal findings of this research. The reader is referred to the individual sections for further details.

- In furniture mock-up tests involving a wide range of fabrics and paddings, the best of the experimental cigarettes tested had considerably lower ignition propensities than previously-tested commercial cigarettes.
- Three cigarette characteristics were found to reduce ignition propensity significantly: low tobacco density, reduced circumference, and low paper permeability. Even larger reductions were achieved with some combinations of these. The tobacco column length, the presence of a filter tip, and citrate content of the paper had effects in limited cases. The tobacco blend had minimal impact on ignition propensity.
- Non-ignitions were often achieved *without* the cigarette self-extinguishing during the test; i.e., many cigarettes burned their full length without igniting the substrate.
- Some of the best performing experimental cigarettes had tar, nicotine, and CO yields that were comparable to typical commercial cigarettes.
- Single embodiments of each of five patented cigarette modifications also reduced ignition propensity. These included variations in the paper, an additive to one location of the tobacco column, an additive throughout the tobacco column, and an additive to the exterior of the paper.
- Ignition results from the mini-mockup apparatus correlate very well with corresponding data from experiments with chairs made with the same fabrics and padding materials.
- The physics of the ignition process is a function of both the cigarette and the substrate. Therefore, an accurate ignition propensity measurement apparatus must involve the two components.
- Intrusive probes of the ignition process (e.g., thermocouples, heat flux gauges) perturb the delicately balanced system; but, if they are small and well-selected, the induced errors can be estimated. With care, (non-intrusive) infrared imaging can be used to study the thermal profiles on non-igniting or igniting substrates.
- An approximate correlation exists between the coal area and ignition propensity. Peak coal surface temperatures (and thus peak heat fluxes) did not vary sufficiently to demonstrate a correlation with ignition tendency for the cigarettes tested.
- Oxygen depletion in the vicinity of the ignition site is important during the ignition process, but is sufficiently similar for all cigarettes examined so as not to account for their relative ignition propensities.
- It is possible to construct a complex computer model of the smoldering combustion of a cigarette and the response of an idealized substrate. With all its simplifications, this model is sufficiently realistic to manifest key physical features of the ignition process and to reproduce some of the cigarette characteristics that do and do not affect ignition propensity. Thus, the model could potentially be used to screen possible combinations of (included) characteristics that offer increased fire safety. At present, however, the model is very slow and not user-friendly.
- The current, mini-mockup methods are valid for *research* measurements of the ignition propensity of cigarettes. However, their use in a *standard* test method of cigarette performance is compromised by the variability in the commercial fabrics and paddings used in the mockup.
- Several alternative candidate test methods for measuring the cigarette ignition propensity of soft furnishings were evaluated; none were usable in their current state of development. Two viable approaches to cigarette testing are proposed. The first modifies the existing mini-mockup procedure using specially-prepared, well-controlled fabrics. The second uses a non-reactive substrate at variable temperature to determine the minimum needed cigarette heat-loss rate for extinguishment. Both need further development.

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## Section 8

# Priority Further Research Directions

## Contents for Section 8

# Priority Further Research Directions

In any closed-end research effort such as this one, there are many ideas that cannot be pursued and others that evolve during the project. The following is a tabulation of those studies whose results are important to a sound understanding of the cigarette/furniture ignition phenomenon and to realization of the research into practical usage.

## Test Method Development and Baseline Data

Both cigarette manufacturers and the public need a test to determine how well improved cigarettes perform. The test should be simple enough to be used as part of a quality assurance program. The development of such a test was intended to be part of the Technical Study Group program. This research has indicated directions for such a method; however, the time frame was too short for complete development. Three promising approaches are:

- Non-smoldering (inert) substrate testing. Studies with cigarettes laid on non-reactive surfaces indicated the potential for differentiating between moderate and low ignition propensity cigarettes. Heating of, e.g., a glass plate or frit allows adjusting the pass/fail criterion. The glass plates could be easily standardized and re-used after cleaning.
- Surrogate reactive substrate testing. The weight loss of multiple layers of $\alpha$-cellulose paper had appeared promising. However, the paper did not differentiate well among the moderate and low ignition propensity cigarettes. Some addition of smolder-enhancing ions could make this approach work.
- Controlled substrate testing. The poor reproducibility with this system has been due to inter- and intra-bolt variation in the fabrics and paddings. Selected fabrics could be scoured and then treated with controlled levels of smolder-enhancing ions. For readily-ignitable fabrics, the fabric dominates the substrate ignition potential. Padding materials would, however, still be carefully selected. The performance of the resulting "standardized" substrates would then be calibrated using cigarettes of varied and known ignition propensity. Testing would be performed using mini-mockups. This area requires a more detailed study of the correlation between alkali metal ion content and smoldering ignition propensity of a fabric.

## Experimental Cigarette Testing

The current research has indicated positive directions for reducing cigarette ignition propensity. Research is needed on more combinations of these factors, especially lower tobacco content and modified paper permeability and thickness. Variations selected using the computer model should also be studied.

## Baseline Performance Data

When a test method is completed, performance data for current market cigarettes should be generated as a baseline. These data could then be compared to analogous future-year cigarette performance data.

## Broader Investigation of Ignition Physics

Extensive research is needed to better measure and define the effect of the substrate on the cigarette's ignition propensity. Specific aspects are:

- characterization of the kinetics of the substrate/cigarette interaction and its impact on ease of ignition, and determination of the thermophysical properties of various substrates;
- more detailed measurement of the heat generation of smoldering cigarettes and components of heat transfer

(radiation, convection, conduction);

- examination of a wider range of experimental cigarettes and substrates; and
- measurement of cigarette ignition in crevices of soft furnishings.

## Ignition Model Predictions

The studies of the physics of the ignition process have been used to guide the development of a first-cut computer model of the ignition process. The model itself is operational, but would benefit from key improvements to correct expedient, but necessary simplifications.

The desirable upgrades to the cigarette model include:

- multi-step tobacco pyrolysis and combustion, rather than simply one-step char combustion, including changes in the kinetics that result from paper modification;
- inclusion of free moisture and combustion-generated water;
- more realistic movement of air and combustion gases within the cigarette; and
- detailed paper behavior (changes in permeability and combustibility) as a function of temperature.

Beneficial improvements to the substrate model are:

- two-layer (fabric plus padding) construction;
- heat-induced reactivity; and
- crevice geometry capability.

The computer programs should then be made more time-efficient to permit a large series of runs with parametric variations of cigarette and substrate variables.

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## Section 9

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