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A COMPARISON OF THE HUMAN SMOKING PATTERNS OF THREE CIGARETTE DESIGNS

REPORT NO. RD.1698 RESTRICTED

11.9.1979

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Group Research & Development Centre,
British-American Tobacco Co. Ltd.,
SOUTHAMPTON.

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11th September 1979.

A COMPARISON OF THE HUMAN SMOKING PATTERNS OF THREE CIGARETTE DESIGNS

(Report No. RD.1698 Restricted)

SUMMARY AND RECOMMENDATIONS

Smokers from GR&DC were recruited to smoke three types of experimental cigarettes. Each cigarette used a particular design feature to achieve similar delivery levels (standard smoking: TPM 18 mg, Nicotine 1.1 mg). These were:

highly efficient filter

highly permeable paper

ventilated filter.

Smoking patterns were recorded and the puff duplicator used to estimate actual deliveries of TPM, nicotine and carbon monoxide. The main conclusions are:

The cigarette with the highly efficient filter was smoked less intensely and delivered less TPM and nicotine but more carbon monoxide than the other two.

The cigarette with highly permeable paper delivered marginally more smoke, TPM and nicotine but less carbon monoxide than the cigarette with a ventilated filter.

These results suggest that the cigarette with a highly efficient filter is less likely to be acceptable than the other two designs. However the experiment should be repeated with cigarettes of lower tar deliveries.

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INTRODUCTION

Most cigarettes currently available employ design features which are selected so that the deliveries do not exceed target levels when the cigarettes are smoked under standard conditions. There are three major design features, which can be used either individually or in combination, to manipulate delivery levels; filtration, paper permeability and filter-tip ventilation. All of these are effective methods of matching the deliveries to target levels when smoked by machine. Smokers, however, might find that some combinations were preferred, particularly if they are smokers who tend to compensate for any reduction in delivery which is achieved by the design features described above. There were indications from previous studies, using cigarettes with comparatively high deliveries, that smokers did not appear to work harder to overcome a high draw resistance (1), but increased the amount of smoke taken from a ventilated filter-tip cigarette when compared with the same type of cigarette with an unventilated filter-tip (2).

We have, therefore, tested the three sorts of design using cigarettes which have similar deliveries (in the middle tar range) when smoked by machine. A panel of smokers was recruited and a comparison made of the smoking patterns and, by puff duplication, the deliveries taken from each design.

METHODS

(a) Cigarettes

Cigarettes were manufactured for this study with the specifications and machine-smoked deliveries shown in Table 1. A commercially available brand, STATE EXPRESS 555 FILTER KINGS, was included in the experimental design, as it was a brand smoked regularly by all members of the panel.

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~~Should not the ages be given or preferably summarized by minimum, lower quartile, median, upper quartile and maximum?~~

S.P.y'cl.

TABLE 1

CIGARETTE SPECIFICATIONS AND DELIVERIES WHEN SMOKED BY MACHINE

Cigarette Code		L245	L246	L247	STATE EXPRESS 555
Tobacco rod length	(mm)	64	64	64	64
Tobacco blend		FC Blend 72			FC Blend 48
Circumference	(mm)	25.1	24.8	24.9	24.9
Filter-tip material		CA	CA	CA	CA
Filter-tip length	(mm)	20	20	20	20
Overtip length	(mm)	24	24	24	24
Overtip perforated		No	No	Yes	No
Pressure drop of filter	(cm W.G.)	5.0	8.7	7.3	5.0
Paper permeability	(CORESTA Units)	112	16	19	48
Overall draw resistance (17.5 ml/sec)	(cm W.G.)	10.9	16.2	12.3	10.1
PMWNF	(mg)	14.1	15.9	15.6	18.1
TPM	(mg)	18.3	19.1	17.9	22.1
TNA	(mg)	1.2	1.0	1.1	1.5
Carbon Monoxide	(% v/v)	3.7	5.4	4.1	4.6
Carbon Monoxide	(mg)	13.7	20.7	16.3	17.1
Puff number		9.3	9.4	9.8	9.3
TPM to nicotine ratio		15.8	18.7	15.8	14.9

(b) The Subjects

Eighteen subjects, 9 male and 9 female were recruited from the laboratory staff of GR&DC. All subjects were regular smokers of middle tar brands who had previously participated in our smoking behaviour studies and were familiar with our equipment and practices.

number of times after itself and each of the other designs . are equal

(c) Experimental Design

Initially each subject smoked three examples of STATE EXPRESS 555 FILTER KINGS on separate occasions. This was to refamiliarise the subjects with the experimental conditions which were changed slightly due to modifications to the laboratory. A closed circuit television system was used for surveillance in place of the one-way mirror used previously. The introduction of the television into the controlled environment room may have had some curiosity value and hence caused some disturbance of smoking behaviour. It should be noted that any difference detected between STATE EXPRESS 555 and any of the experimental cigarettes could be due to the fact that STATE EXPRESS 555 were smoked before the others.

The subjects then smoked four examples of each of the three experimental cigarettes in a balanced order that would allow unconfounded estimation of the differences between the cigarettes. The subjects smoked the cigarettes so that each of the three designs was smoked an equal number of times after itself and each of the other designs. This allowed investigation of any carry-over effects from the previous session.

(d) Experimental Procedure

The experimental procedure was essentially the same as described previously (3), using the controlled environment room (4), and the Smoking Analyser and Data Logger (5). After the subject had smoked the cigarette, the butt length was measured and recorded. The filter-tip was cut from the cigarette butt and prepared for nicotine analysis.

(e) Data Retrieval

The magnetic tapes from the Smoking Analyser and Data Logger were translated into reduced format paper tapes and printouts of the data

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obtained by reading the paper tapes on a teletype. The reduced format paper tapes were also read through the Argus 500 in-house computer to be reformatted on magnetic tape in a standard IBM compatible format. This magnetic tape was then copied to another so that all the data were held on a single file in preparation for statistical analysis.

The teletype printouts were organised so that the smoking pattern data for each replicate of each subject could be compared. One smoking pattern from the three or four replicates of each of the four cigarette types smoked was selected for each subject. This was the one which was closest to the average way that the subject smoked the particular cigarette type. The criteria used for this selection were the total volume of smoke drawn, the number of puffs used to draw it and the butt length. Paper tapes, of the selected smoking patterns were prepared in duplication format and used to control the puff duplicator to smoke cigarettes of the appropriate types. Each paper tape was used to smoke four cigarettes on the duplicator. Thus a total of 72 tapes were prepared and 288 cigarettes smoked on the puff duplicator.

SMOKING INTENSITY INSIDE AND OUTSIDE THE LABORATORY

As a supplementary experiment the subjects who had participated in the laboratory study were asked to smoke the experimental cigarettes and STATE EXPRESS 555 outside the laboratory.

Packs of 20 cigarettes were issued to the subjects together with a metal cigarette box. After smoking each cigarette the subjects were asked to place the cigarette butt in the metal box and to return the box to the laboratory when they had smoked the issued cigarettes. The subjects were not asked to smoke the experimental cigarettes exclusively.

When the tins containing the butts were returned to the laboratory, the butts were counted, their lengths measured and the filter tips cut from the butts. The filter tips were prepared for nicotine analysis.

RESULTS

The smoking pattern data have been averaged across all subjects and all replicates for the four cigarette types smoked. These data are shown as Table 2.

The results of the smoking pattern duplication are shown as Table 3, where the data have been averaged for all subjects and replicates.

A comparison of the lengths of the cigarette butts and the amounts of nicotine remaining in the filter tips of the cigarettes smoked within the laboratory and outside it are shown in Table 4. The delivery of nicotine to the smokers has been estimated by using the average filtration efficiency figures found by puff duplication.

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TABLE 2

AVERAGE SMOKING PATTERN DATA

Measurements		Cigarette Code			
		L245	L246	L247	STATE EXPRESS 555
Total volume	(ml)	492	422	481	483
Average volume	(ml)	43.3	37.3	41.7	41.7
Total duration	(sec)	24.6	24.5	25.3	23.8
Average duration	(sec)	2.16	2.16	2.19	2.05
Total interval	(sec)	372	369	384	390
Average interval	(sec)	35.8	35.8	36.6	36.9
Lit draw resistance	(cm W.G.)	15.8	22.2	17.5	17.3
Total time alight	(sec)	396	393	410	413
Puff number		11.4	11.3	11.5	11.6
Butt length	(mm)	32.5	32.4	32.9	32.7
Tip nicotine	(mg)	0.73	1.27	0.89	0.83

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TABLE 3

AVERAGE DELIVERIES BY PUFF DUPLICATION

Measurements		Cigarette Code			
		L245	L246	L247	STATE EXPRESS 555
Original tip nicotine	(mg)	0.75	1.30	0.95	0.85
Duplicated tip nicotine	(mg)	0.83	1.19	0.88	1.13
Delivered nicotine	(mg)	1.57	1.22	1.37	2.03
Delivered TPM	(mg)	19.5	16.5	17.9	24.7
Delivered carbon monoxide	(%)	2.6	4.5	3.2	3.6
Delivered carbon monoxide	(mg)	16.1	23.9	19.4	22.1
Original butt length	(mm)	33.1	32.9	32.6	32.7
Duplicated butt length	(mm)	33.4	33.1	33.1	31.8
Filtration efficiency (nicotine)	(%)	36	49	39	36
TPM to nicotine ratio		12.4	13.5	13.0	12.1

TABLE 4

COMPARISON OF CIGARETTE BUTTS SMOKED IN THE LABORATORY AND OUTSIDE

		L245		L246		L247		STATE EXPRESS 555	
		Laboratory	Outside	Laboratory	Outside	Laboratory	Outside	Laboratory	Outside
Filter tip TNA	(mg)	0.76	0.54	1.30	0.94	0.92	0.70	0.79	0.76
Delivery of TNA (calculated)	(mg)	1.44	1.03	1.33	0.96	1.43	1.08	1.41	1.36
% Difference (Laboratory cf outside)		-28		-28		-25		-4	
Butt length	(mm)	32.8	33.5	32.2	33.5	33.1	33.6	32.9	33.8
% Difference (Laboratory cf outside)		+ 2		+ 4		+ 1		+ 3	

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STATISTICAL ANALYSIS OF RESULTS

The statistical procedures used for the analysis of these data together with detailed tables of Analysis of Variance are shown in the Appendix.

Differences between the cigarettes for total and average puff intervals, total and average puff durations, puff number and butt length were small but statistically significant at a high level of confidence. The lit draw resistance was 27% ± 1% greater for L246 (high filtration efficiency) than for L247 (filter tip ventilation) which in turn was 12% ± 1% greater than for L245 (high paper permeability). The total volume of smoke taken from L246 was 13% ± 2% less than taken from L245 and L247 which were very similar.

There was a tendency for more smoke to be taken from early puffs rather than puffs taken further down the cigarette, especially for L245.

The deliveries of TPM and nicotine, measured by puff duplication, were 16% ± 5% and 27% ± 6% more respectively from L245 than from L246. The delivery from L247 was at an intermediate level for both TPM and nicotine. The differences in delivery of carbon monoxide between the cigarettes were in the same order as predicted by the machine smoked deliveries. The highest delivery of carbon monoxide was from L246 and the lowest from L245.

There was no indication that the brand effects were not constant for both sexes or that smoking was affected by the order in which the cigarettes were smoked.

DISCUSSION OF RESULTS

1. Cigarette Design and Smoking Behaviour

The main design differences between the three experimental cigarettes were that the target deliveries were achieved essentially by high permeability paper in L245, high filtration efficiency in L246 and filter-tip ventilation in L247.

Unsolicited comments suggested that the panel of smokers found the experimental cigarettes tolerable but not as pleasant as STATE EXPRESS 555.

From the results of the average smoking pattern data (Table 2) and the statistical analysis of the results, it can be seen that the most outstanding difference between the three types of experimental cigarette was that the lit draw resistance of the L246 cigarette was higher than the other two (and STATE EXPRESS 555). This means that the smokers had to work harder to draw the same volume of smoke from this cigarette than from the others. Although a greater puffing effort was used to smoke L246, the smokers did not draw hard enough to obtain as much smoke, either in total or on average per puff as they did from the other cigarette types.

The closeness of the smoking patterns shown on the L245, L247 and STATE EXPRESS 555 cigarettes was remarkable. The design of the STATE EXPRESS 555 cigarette is in many ways intermediate between L245 and L247 but with slightly higher deliveries of TPM and nicotine.

Puff duplication of about one quarter of the recorded data showed that smokers did take more TPM and nicotine from the STATE EXPRESS 555 than from the experimental cigarettes. Of the three experimental cigarettes L245 was smoked with slightly higher intensity (as defined

were smoked.

by total puff volume) than L247 and yielded slightly higher deliveries of TPM and nicotine. L246 was smoked with the lowest intensity and delivered the lowest amounts of TPM and nicotine. The design of L246 which had no filter-tip ventilation and the least permeable paper of the three designs studied, delivered the largest amount of carbon monoxide. Of the other two experimental designs, the L245, with the highest paper permeability, delivered less carbon monoxide than L247 with the filter-tip ventilation.

The previously recorded observation (3) that human smokers obtain lower TPM to nicotine ratios than obtained by standard machine smoking has been confirmed here.

Analysis of the smoking pattern data showed that the intensity of smoking L245 was higher in the first few puffs than for the other cigarette types. This may have been due to the fact that its puff by puff deliveries are initially lower than the other cigarettes, as shown in Table 5 in the Appendix. The reason for the lower puff by puff delivery is that the degree of ventilation on L245, as measured by the puff duplicator technique (6) is between 50-60%, depending on flow rate, when compared with L246, which has 10-26% ventilation. Both L247 and STATE EXPRESS 555 have about 30-40% ventilation (a table of ventilation results is shown in the Appendix as Table 6).

These results indicate that there was little difference in the way L245 and L247 were smoked. Although the smokers took very similar volumes of smoke from L245 and L247, they received marginally higher deliveries from L245 and used less puffing effort* to do so. This suggests that L245 may have marginal advantages over L247.

*This can be calculated by multiplying the lit draw resistance by the average puff duration and the puff number shown in Table 2.

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2. Laboratory Smoking

The difference in nicotine delivery (as determined by butt analysis) between smoking the experimental cigarettes in the laboratory and outside it was in the range 25-30%, lower amounts of nicotine being taken outside the laboratory. It has been previously observed (7, 9) that cigarettes tend to be smoked more intensely in the laboratory than outside. The difference between smoking STATE EXPRESS 555 inside the laboratory and outside it was less than 5%, but again, more nicotine was taken from cigarettes smoked in the laboratory. It is only possible to speculate on the reasons for the small difference for the STATE EXPRESS 555 since differences of at least 25% have been repeatedly found for other commercial cigarettes (8).

The differences in butt lengths between the cigarettes smoked inside and outside the laboratory were much less; in all cases less than 5%. Further discussion of laboratory smoking is given in the Appendix (Section 3).

3. General Comments

On the basis of the smoking behaviour studies described in this report, the cigarette with the high pressure-drop filter is likely to be the least acceptable of the three designs examined.

A further experiment of this kind, but using cigarettes with lower deliveries, which will of necessity exaggerate the design differences, might show a greater separation of smoking patterns and deliveries to human smokers. However such a study cannot be carried out until a new sample is identified and recruited. It would be necessary to use a panel of smokers who normally smoke "low tar" or "low to middle tar" cigarettes regularly, in order to obtain a realistic and representative result.

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APPENDIX

1. VENTILATION

Table 5 shows the degree of ventilation at various flow rates measured by the puff duplicator technique (6) for the four cigarettes used in this study.

TABLE 5

DEGREE OF VENTILATION AT DIFFERENT FLOW RATES

(Expressed as percentage, Average of 6 cigarettes tested)

Flow Rate (ml/sec)	50	45	40	35	30	25	20	15	10
L245	60.4	59.6	58.0	56.9	55.7	53.6	51.5	61.3	*
L246	25.8	24.2	23.0	21.2	17.3	17.2	17.5	14.0	9.0
L247	38.8	37.6	36.0	34.6	34.0	32.8	31.5	29.3	39.0
STATE EXPRESS 555	40.8	38.9	37.0	35.4	34.3	32.4	30.0	28.0	29.0

* Indicates reading unobtainable.

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2. TPM DELIVERY

TABLE 6

PUFF BY PUFF DELIVERIES OF TPM

(Expressed in mg average of 5 cigarettes smoked)

Puff Number	5	6	9	12
L245	3.1	8.9	17.2	31.5
L246	4.7	11.5	19.7	27.5*
L247	4.6	9.0	17.2	31.1
STATE EXPRESS 555	4.8	10.5	20.2	32.2

* Only 11 puffs taken.

Smoking Conditions (chosen to simulate human smoking)

Puff Volume 52 ml

Puff duration 2.0 sec

Interval 33 sec

Puff shape Sinusoidal

Free smoking

3. LABORATORY SMOKING

As already stated, shorter butts were left from cigarettes smoked inside the laboratory. This difference in butt length, which represents 1-2 mm of tobacco rod length, is insufficient to account for the differences in filter-tip nicotine content between the cigarettes smoked inside and outside the laboratory. The difference must, therefore, be related to the number of puffs, the volume of the puffs or spacing of the puffs taken inside and outside the laboratory. These results, therefore, confirm that the cigarette holder used in the laboratory has little effect on the butt lengths.

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The cigarette holder does, however, have some resistance to draw which is added to the draw resistance of the cigarette so that the combined draw resistance of the cigarette and the holder must be higher than the cigarette alone. The results of the main part of this experiment, and a previous experiment (1) show that high draw resistance is a feature of cigarette design which is associated with a reduction in smoker's puff volumes. It would, therefore, be expected that the volumes of smoke per puff, and the total volume of smoke drawn would tend to be lower on cigarettes smoked in the laboratory through a holder. As the intensity of smoking was clearly higher in the laboratory than outside, the laboratory conditions must influence the smoking behaviour. This may be because the smokers are alone and have little else to do except smoke, or the environment and procedures are stressful. There is little evidence to suggest that the controlled environment room is stressful, in fact some smokers have been known to become drowsy.

Another possibility is that the cigarette holder modifies the smoke in such a way that it becomes less "effective" so that the smokers need to take more smoke. There is some tentative evidence that at flow rates higher than 20 ml/sec, the orifice-plate in the cigarette holder causes the smoke particles to increase in size and weight, thereby increasing their chances of filtration by impaction and interception. However, this effect would not seem to be sufficient to explain the 25% difference between smoking inside and outside the laboratory.

The phenomena associated with the orifice-plate cigarette holder needs to be further investigated, for example by comparing the smoking patterns of a panel of subjects smoking the same brand of cigarettes

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through cigarette holders, both with and without an orifice plate. A 5 mm section of filter could be cut from the end of a cigarette and used as the resistance to flow between the arms of a cigarette holder. If there were no differences in smoking pattern it would strongly suggest that the increased intensity of smoking demonstrated in the laboratory was due to the solitude and lack of something to occupy the hands and mind. Smoking outside the laboratory is probably an unobtrusive accompaniment to other activities, whereas in the laboratory it is the main event.

4. EXPERIMENTAL DESIGN

18 volunteer subjects (9 male and 9 female) were recruited from the staff of GR&DC. Each subject smoked a STATE EXPRESS 555 on each of their first three sessions. For the next 12 sessions each subject smoked each of the three experimental cigarettes four times as shown in Table 7. This design has several noteworthy features. Each cigarette was smoked 6 times for each session number (this is not quite true as sessions 7 and 8 of subject 6 occurred in the wrong order). This means that the effects of the cigarettes and session number are orthogonal. Thus estimates of the differences between the cigarettes would not be affected by changes over the experimental period.

It has been suggested that the way the cigarette is smoked might be influenced by which cigarette was smoked in the previous session. This is called a carry-over effect. If this were the case then a design would be wanted allowing unbiassed estimation of the direct effects of the cigarettes and of the residual variances. Thus each cigarette type was preceded by itself and each other cigarette type in the subject's

re-interpreted

made from FC ground -12

15 0.7 or from another ground?

and grounds

varying and grounds

previous session 22 times. Carry-over effects are also worth investigating for their own sake, since if they are found to be of practical significance, then this will have consequences for the design of future experiments and past experiments may have to be re-interpreted.

In the next section the analysis of the data is described and it was decided to use only the last 11 sessions for each subject. Thus for each subject 4 sessions on two of the cigarettes and 3 on the other were used. The design would have been improved by including an extra session where the smoker smoked the same brand as in session 4. In this experiment the differences between 3 cigarette designs made from FC blend 72 with machine deliveries of around 18 mg TPM and 1.1 mg TNA are investigated. Does this experiment have any information about differences between the 3 designs at, say 15 mg TPM and 0.9 mg TNA or from another blend? Readers may be tempted to extrapolate the results from the range of the experiment with little justification. If the aim of the experiment was to investigate differences between the cigarette design over a wide range of tar and nicotine levels and blends then a factorial experiment with, say 4 tar levels and various blends should have been used. Each smoker could have smoked each cigarette once. As it stands the scope for applying the results of this experiment is rather narrow.

STATISTICAL ANALYSIS

5. METHODOLOGY

Let Y be an observation of some parameter made during session number X. The the following model was fitted to the observations from sessions 5 to 15:

$$(B + C) * S/P + B.C + X$$

using the notation of Wilkinson and Rogers (10).

x man

B denotes the direct cigarette effect and is fixed with 3 levels: L245, L246 and L247.

C denotes the carry over cigarette effect and is fixed with 3 levels: L245, L246 and L247.

S denotes the sex effect and is fixed with 2 levels: male and female.

P is the smoker effect and is nested within sex having 9 levels within each.

It was assumed that P was a random effect i.e. the inferences from this experiment refer not only to the smokers who actually took part in the experiment, but also to a larger population of which we regard the subjects as a random sample. This matter has been discussed at some length in (11) and thus discussion here will be limited. The smokers of GR&DC are probably quite dissimilar to the general public concerning the general level of smoking i.e. butt length, puff number, volume etc. This may be because of the free issue of STATE EXPRESS 555. However our main interest lies not with the level of these parameters, but with the differences between these parameters with the 3 cigarette designs. It does not seem unreasonable that these differences for GR&DC smokers might be quite typical of those for the general public, thus it is probably valid to extrapolate to a wider population of smokers. In fact it seems more valid than the extrapolation from the artificial smoking circumstances in which the experiment was conducted.

The above model is nearly orthogonal and so the order in which the effects were fitted was not important. Thus each effect was treated as though it were the last one fitted. The statistical analysis was peformed using the MANOVA procedure of SPSS (12).

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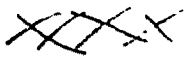
In simple terms the various effects were tested as follows. Differences between the direct effect of the 3 cigarettes were tested by comparison with the consistency of the differences for all the smokers i.e. the cigarette mean square is compared to the cigarette x smoker within sex mean square by an F test. The interaction between sex and the direct cigarette effect, the carry over effect of the cigarettes and its interaction with sex were analogously tested. The differences between the sexes were tested by comparison with the differences amongst smokers of the same sex. The interaction between the direct and carry over effects of the cigarettes was tested using the residual mean square, and thus assuming that this interaction was the same for all subjects. Any trend over the experiment was also tested using the residual mean square and so it was assumed that this was the same for all subjects.

The volume of smoke taken by each smoker was measured puff by puff. It was thought that the cigarettes might vary in the puff by puff distribution of the volume. For example the cigarette with highly porous paper, L245, could present the smoker with highly diluted smoke in his early puffs and more concentrated smoke in the later ones. Thus the smoker might tend to take smaller puff volumes in later puffs. Comparisons are difficult as the number of puffs per session are not constant. The following approach was adopted.

Let V(p) be the cumulative volume of smoke taken after the p'th puff of a cigarette. Suppose the form of V(p) is known except for a number of unknown parameters which vary from session to session. Then desirable properties for V(p) are:



(a) flexible enough to describe a wide variety of actual cumulative puff volumes.

(b) simplicity and paucity of unknown parameters.

(c) unknown parameters should be easily interpreted.

(d) V(p) should be strictly increasing i.e. V(p+1) > V(p) for all p.

Polynomials were rejected as they need not be strictly increasing. However inverse linear polynomials are fairly simple, having only 2 parameters which are easily interpreted, and are strictly increasing. Fitting inverse linear polynomials it was found that generally they did describe the cumulative puff volumes very well except for the final puff which tended to be overestimated.

$$\text{Let } V(p) = \frac{p}{a + bp}$$

Then it is easily shown that:

1. $V(0) = 0$.
2. $V(p)$ is approximately p/a for small p.
3. If $b = 0$ then $V(p)$ is a straight line through the origin.
4. If $b < 0$ then the volume of smoke taken at successive puffs decreases.
5. If $b > 0$ then the volume of smoke taken as successive puffs increases.
6. The curvature of the curve (minus the second derivative) is $2ab/(a + bp)^3$, which was approximated by $2b/a^2$.

Thus $1/a$ is a measure of the size of the early puffs and b/a^2 is a measure of the tendency to decrease the puff volume whilst smoking a cigarette.

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For a particular smoking session an inverse linear polynomial was fitted to the realised cumulative puff volume function as follows. Let us rewrite V(p) as

$$\frac{1}{V(p)} = \frac{a}{p} + b.$$

The right hand side is a linear function of (1/p). The statistical package GLIM (13, 14) was used to fit (1/p) assuming Gaussian errors and using the reciprocal link function. This assumed that the errors were not serially correlated, which was clearly not the case. This meant the standard errors of the estimate of a and b were meaningless and the estimates of a and b were not optimum in any sense. However the curve obtained was a very reasonable description of the realised curve. For each subject x cigarette combination one of the four sessions was selected using random numbers and an inverse linear polynomial fitted to the realised cumulative puff volume function. Both the slope at zero and the curvature were analysed fitting the following model:

$$B * (S/P).$$

From the four sessions during which each subject smoked each brand, the most typical was chosen and these were duplicated four times. The average TPM, nicotine and carbon monoxide deliveries were taken as estimates of the actual amounts delivered to the smoker. These three parameters were analysed by fitting the same model as for the cumulative puff volumes.

Before analysing any parameter a choice must be made whether to use the raw scale or to transform the scale. Several factors have to be taken into account. The most important is to obtain results which may

be easily understood by the mathematically unsophisticated reader. There are two kinds of comparisons in everyday language:

1. $x = y + 4$.

2. $x = 2y$.

The former says how much has to be added to equal y and the latter how much has to be multiplied. Most statistical procedures assume the response is the sum of systematic effects and random effects. Thus it is easier to make comparisons based on differences. However if the response is assumed to be the product of systematic effects and random effects, the logarithm of the response is the sums of the logarithms of these effects. Thus a multiplicative model is easily fitted by analysing the log-transformed response. Multiplicative comparisons have the added advantage that comparisons across parameters can be compared.

Our primary concern is with the differences between the three cigarettes. The precision of the estimates of the differences are obtained from the interaction between the subjects and the cigarettes. This interaction may be due to two components: the smoker's individuality and a systematic element due to scale. For example, ignoring individuality, say the number of puffs taken on cigarette B is 10% more than that on A. A smoker who on average takes 10 puffs on A will take 11 puffs on B, whilst a smoker who takes 20 puffs on A will take 22 puffs on B. Thus if the parameter were analysed on the raw scale the interaction would be inflated and the analysis would be wasteful of information.

Two further assumptions were made: constancy of the variance components and that the random effects were normally distributed. It is not unusual to find that variability increases with size and the coefficient

mean
Λ

of variation may be more stable than the standard deviation. Also samples tend to be positively skewed rather than symmetric. If both of these are the case, matters are usually improved by the log-transform.

For most parameters there was little indication about which, if any, transformation should be used. In these cases ease of communicating the results was the prime factor. However for lit pressure drop there was strong evidence that the underlying distribution was not normal and the variance increased with size. This was not the case for the log-transformed data. Thus it was decided to analyse the logarithms of all parameters.

6. RESULTS

The analysis of variance tables for Total Interval, Mean Interval, Total Duration and Mean Duration are given in Table 8; those for Proportion Puff Time (Duration/(Duration + Interval), Puff Number, Butt Length and Lit Pressure Drop (Total Pressure/Total Duration) are given in Table 9; and those for Total Volume, Mean Volume and Intensity (Total Volume/Total Duration) in Table 10.

Differences between Cigarettes

The estimated differences between cigarettes and their standard errors are given in Table 11. The differences between the 3 cigarettes for total duration, mean duration, proportion puff time and butt length were very small. Moreover the precision of these comparisons was such that it can be stated with a high degree of confidence (90%) that differences were small (less than 5%). There was a tendency for there to be longer mean intervals and more puffs with the ventilated tip cigarette (L247) than the other two. This resulted in L247 having 4% longer total intervals than the others with a 95% confidence interval of (2%, 6%).

The lit pressure drop of the high filtration cigarette, L246, was an estimated 27% more than that of L247 with a 95% confidence interval of (23%, 30%). L247's lit pressure drop was an estimated 12% more than that of L245 (high paper porosity) with a 95% confidence interval of (9%, 15%). The total volume of smoke taken from L245 and L247 was very similar and was 16% greater than that taken from L246 with a 95% confidence interval of (11%, 20%). Mean volume and intensity were similarly affected.

The fitted slopes at zero and curvatures for the cumulative puff volumes are given in Tables 12 and 13 respectively. Smaller volumes of smoke were taken from the initial puffs of L246 than both L245 and L247. Though the difference between L245 and L247 was marginally statistically significant, the difference was not large. No statistically significant difference could be detected between the curvatures of the cumulative puff volumes. A priori it might be expected that the cigarette with high paper porosity, L245, might exhibit greater curvature than both L246 and L247. The hypothesis that L245 was the same as L246 and L247 was marginally significant ($p=0.03$, one sided t-test). Thus it appears that the tendency to reduce the puff volumes during a smoke is greater for L245 than L246 and L247. The average cumulative puff volume curves are shown in Figure 1. The curves for L245 and L247 are very similar, and quite distinct from that of L246.

The TPM delivery as estimated from duplication is given in Table 14. 16% more TPM was taken from L245 than from L246 with a 95% confidence interval of (6%, 26%). L247 occupied an intermediate position, without being clearly distinguishable from either L245 or L246. Table 15 gives

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the estimated deliveries of nicotine. Delivery was 27% more from L245 than from L246, with a 95% confidence interval of (15%, 40%). L247 again occupied an intermediate position, being marginally significantly different from both L245 and L247. The estimated CO deliveries are given in Table 16. The differences between the cigarettes are very similar to those predicted by the machine CO deliveries.

Interaction between Sex and Direct Brand Effects

For no parameter was there any indication that the direct brand effects were not the same for both sexes.

Carry-Over Brand Effects

The estimated carry-over effects and their standard errors are given in Table 17. It is seen that the effects are at most small and not statistically significant. This was the case for both sexes. The direct effects of the cigarettes was not affected by the previous cigarette.

Differences Between the Sexes

Estimates of differences between the sexes are given in Table 18. None of these differences were statistically significant. The experiment has provided very little information concerning sex differences and the data are quite consistent with there being large differences.

Trends Over the Experiment

Table 19 summarises the trend estimates. In all cases the trends were small i.e. less than 1% per session with a high degree of confidence. The cigarettes were smoked less intensely as the experiment progressed and the lit pressure drop decreased by an estimated 0.5% per session.

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TABLE 7

CIGARETTE SMOKED IN EACH SESSION FOR EACH SUBJECT

Session Number	Subjects																	
	Females									Males								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE
2	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE
3	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE	SE
4	5	5	5	7	6	7	7	6	5	6	7	6	6	7	7	5	5	6
5	5	5	6	5	5	5	7	6	7	7	6	5	6	7	6	6	7	7
6	6	7	7	5	5	6	5	5	5	7	6	7	7	6	5	6	7	6
7	6	7	6	6	7	6	5	5	6	5	5	5	7	6	7	7	6	5
8	7	6	5	6	7	7	6	7	5	5	5	6	5	5	5	7	6	7
9	7	6	7	7	6	5	6	7	6	6	7	7	5	5	6	5	5	5
10	5	6	7	7	7	5	7	5	6	7	5	6	6	6	5	5	6	7
11	5	6	7	5	6	7	6	7	5	7	5	6	7	5	6	6	7	5
12	6	7	5	5	6	7	5	6	7	6	7	5	7	5	6	7	5	6
13	7	5	6	7	7	5	5	6	7	5	6	7	6	6	5	7	5	6
14	7	5	6	6	5	6	6	7	5	5	6	7	5	7	7	6	7	5
15	6	7	5	6	5	6	7	5	6	6	7	5	5	7	7	5	6	7

SE - STATE EXPRESS 555. 5 - L245. 6 - L246. 7 - L247.

KEY TO TABLES 8-20

Statistical Significance

N.S.	$p > 0.1$
*	$p < 0.1$
**	$p < 0.05$
***	$p < 0.01$
****	$p < 0.001$

TABLE 8

ANALYSIS OF VARIANCE TABLES FOR TOTAL INTERVAL, MEAN INTERVAL, TOTAL DURATION AND MEAN DURATION

Source	D.F.	Total Interval			Mean Interval			Total Duration			Mean Duration		
		MS x 10^{-4}	F	P	MS x 10^{-4}	F	P	MS x 10^{-4}	F	P	MS x 10^{-4}	F	P
Cigarette	2	343	7.2	***	77	0.9	N.S.	176	1.1	N.S.	19	0.2	N.S.
Cigarette x Sex	2	31	0.6	N.S.	56	0.7	N.S.	89	0.6	N.S.	87	0.9	N.S.
Cigarette x Subjects within Sex	32	47			85			155			94		
Previous Cigarette	2	118	2.0	N.S.	122	0.5	N.S.	49	0.3	N.S.	23	0.2	N.S.
Previous Cigarette x Sex	2	43	0.7	N.S.	71	0.3	N.S.	105	0.6	N.S.	14	0.1	N.S.
Previous Cigarette x Subjects within Sex	32	60			243			181			107		
Sex	1	294	0.1	N.S.	563	0.1	N.S.	2175	0.4	N.S.	6986	1.2	N.S.
Subjects within Sex	16	3602			9091			5973			5753		
Cigarette x Previous Cigarette	4	15	0.3	N.S.	340	0.2	N.S.	158	1.3	N.S.	73	0.9	N.S.
Session Number	1	23	0.4	N.S.	78	0.5	N.S.	337	2.8	*	34	0.4	N.S.
Residual	103	58			172			120			82		

Puff Number Butt Length Draw Pressure Drop

TABLE 9

ANALYSIS OF VARIANCE TABLES FOR PROPORTION PUFF TIME, PUFF NUMBER, BUTT LENGTH AND LIT PRESSURE DROP

Source	D.F.	Proportion Puff Time			Puff Number			Butt Length			Lit Pressure Drop		
		MS x 10^{-4}	F	P	MS x 10^{-4}	F	P	MS x 10^{-4}	F	P	MS x 10^{-4}	F	P
Cigarette	2	27	0.2	N.S.	88	1.0	N.S.	60	2.4	N.S.	17396	295.7	****
Cigarette x Sex	2	15	0.1	N.S.	47	0.5	N.S.	3	0.1	N.S.	56	1.0	N.S.
Cigarette x Subjects within Sex	32	121			85			25			59		
Previous Cigarette	2	153	0.6	N.S.	5	1.0	N.S.	18	0.4	N.S.	183	0.9	N.S.
Previous Cigarette x Sex	2	105	0.4	N.S.	73	0.5	N.S.	27	0.6	N.S.	393	1.9	N.S.
Previous Cigarette x Subjects within Sex	32	271			85			49			208		
Sex	1	3347	0.3	N.S.	1365	0.5	N.S.	1355	0.6	N.S.	91	0.0	N.S.
Subjects within Sex	16	11939			3024			2114			5116		
Cigarette x Previous Cigarette	4	69	0.4	N.S.	48	0.5		32	1.1	N.S.	10	0.3	N.S.
Session Number	1	152	0.8		158	1.8		19	0.1	N.S.	334	8.7	***
Residual	103	180			88			29			38		

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TABLE 10

ANALYSIS OF VARIANCE TABLES FOR TOTAL VOLUME, MEAN VOLUME AND INTENSITY

Source	DF	Total Volume			Mean Volume			Intensity		
		MS x 10^{-4}	F	P	MS x 10^{-4}	F	P	MS x 10^{-4}	F	P
Cigarette	2	4265	30.7	****	3707	71.0	****	3291	67.4	****
Cigarette x Sex	2	104	0.7	N.S.	11	0.2	N.S.	116	2.4	N.S.
Cigarette x Subjects within Sex	32	139			52			49		
Previous Cigarette	2	50	0.3	N.S.	25	0.3	N.S.	1	0.0	N.S.
Previous Cigarette x Sex	2	5	0.0	N.S.	115	1.4	N.S.	156	2.5	*
Previous Cigarette x Subjects within Sex	32	182			84			62		
Sex	1	2967	1.4	N.S.	8357	2.5	N.S.	61	0.0	N.S.
Subjects within Sex	16	2070			3324			4959		
Cigarette x Previous Cigarette	4	11	0.1	N.S.	28	0.4	N.S.	34	0.7	N.S.
Session Number	1	7	0.1	N.S.	229	3.4	*	441	8.5	***
Residual	103	120			68			52		

Scheffé's

TABLE 11

DIFFERENCES BETWEEN CIGARETTES

Parameter	Ratios			Standard Error of Ratio
	L245/L246	L245/L247	L246/L247	
Total interval	1.02	0.97	0.95	0.012
Mean interval	1.02	0.99	0.97	0.014
Total duration	1.01	1.01	0.98	0.022
Mean duration	1.01	1.01	0.99	0.017
Proportion puff time	0.99	1.02	1.02	0.019
Puff number	1.00	0.98	0.98	0.016
Butt length	1.00	0.99	0.99	0.012
Lit pressure drop	0.71****	0.90****	1.27****	0.013
Total volume	1.17****	1.03	0.88****	0.021
Mean volume	1.17****	1.05***	0.89****	0.013
Intensity	1.10****	1.04***	0.90****	0.012

Paired comparisons by Scheffé's test (15).

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TABLE 12

CUMULATIVE PUFF VOLUMES: SLOPE AT ZERO (ml/puff)

(i) DATA

	L245	L246	L247	
FEMALES	57	51	55	54
	32	23	32	29
	58	52	51	54
	46	43	56	48
	56	41	47	48
	60	45	60	55
	55	35	49	46
	61	45	46	51
	60	53	56	56
MALES	82	75	71	76
	61	61	62	61
	50	51	60	54
	56	38	49	48
	71	44	59	58
	51	20	52	41
	56	48	48	51
	61	48	55	55
	64	54	46	55
	57.6	45.9	53.0	52.2

(ii) ANALYSIS OF VARIANCE TABLE

Source	SS	DF	MS	F	P
Sex	523	1	523	2.1	N.S.
Subjects within Sex	3933	16	246		
Cigarettes	1243	2	622	16.5	****
Cigarettes x Sex	10	2	5	0.1	N.S.
Residual	1207	32	38		

Estimated standard error of difference between brand means = 2.0.

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TABLE 13

CUMULATIVE PUFF VOLUMES: CURVATURE (10 b/a^2)

(i) DATA

	L245	L246	L247	
FEMALES	22	28	20	23
	4	1	2	3
	14	16	6	12
	6	5	14	8
	18	8	8	11
	13	6	26	15
	17	4	13	11
	11	11	5	9
	21	23	28	24
MALES	17	26	7	17
	12	27	17	19
	26	24	22	24
	13	1	8	7
	51	8	21	27
	18	-4	11	8
	8	4	4	5
	23	12	16	17
	2	6	0	3
	16.4	11.4	12.7	13.5

(ii) ANALYSIS OF VARIANCE TABLE

Source	SS	DF	MS	F	P
Sex	16	1	16	0.1	N.S.
Subjects within Sex	2905	16	182		
Cigarettes	245	2	123	2.1	N.S.
Cigarettes x Sex	105	2	53	0.9	N.S.
Residual	1900	32	59		

Estimated standard error of difference between cigarette means = 2.6.

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TABLE 14

ESTIMATED TPM UPTAKE FROM DUPLICATION (mg)

(i) DATA

	L245	L246	L247	
FEMALES	10.9	14.4	15.4	13.6
	20.4	19.9	21.6	20.6
	13.0	11.8	13.6	12.8
	25.6	16.7	19.5	20.6
	22.5	17.9	19.1	19.8
	15.1	16.6	18.1	16.6
	18.5	16.9	12.1	15.8
	23.3	13.3	16.7	17.8
	15.0	13.3	15.9	14.7
MALES	35.8	25.8	25.1	28.9
	16.7	14.1	15.7	15.5
	20.0	17.7	22.2	20.0
	19.3	15.9	16.8	17.3
	19.0	19.0	19.5	19.2
	14.3	11.9	14.1	13.4
	24.5	18.8	21.8	21.7
	18.1	15.3	18.4	17.3
	18.3	17.4	17.0	17.6
	19.5	16.5	17.9	18.0

(ii) ANALYSIS OF VARIANCE TABLE (log transformed data)

Source	SS	DF	MS	F	P
Sex	0.168	1	0.168	1.4	N.S.
Subjects within Sex	1.854	16	0.116		
Cigarettes	0.197	2	0.099	6.2	***
Cigarettes x Sex	0.003	2	0.001	0.1	N.S.
Residual	0.513	32	0.016		

(iii) RATIOS

L245/L246	L245/L247	L246/L247
1.16***	1.06	0.92

Estimated standard error of ratios 0.04. Paired comparisons by Scheffé's test

TABLE 15

ESTIMATED NICOTINE UPTAKE FROM DUPLICATION (mg)

(i) DATA

	L245	L246	L247	
FEMALES	0.90	0.98	1.13	1.00
	1.66	1.17	1.77	1.53
	1.23	0.82	1.24	1.10
	1.95	1.54	1.39	1.63
	1.73	1.22	1.42	1.46
	1.29	1.32	1.44	1.35
	1.57	1.19	0.91	1.22
	1.87	1.30	1.17	1.45
	1.18	0.87	1.41	1.15
MALES	2.59	1.65	1.73	1.99
	1.46	1.13	1.05	1.48
	1.54	1.26	1.72	1.51
	1.49	1.28	1.42	1.40
	1.95	1.41	1.62	1.66
	1.24	0.98	1.09	1.10
	1.96	1.27	1.61	1.61
	1.25	1.00	1.33	1.19
	1.38	1.52	1.29	1.15
	1.57	1.22	1.37	1.39

(ii) ANALYSIS OF VARIANCE TABLE (log transformed data)

Source	SS	DF	MS	F	P
Sex	0.125	1	0.125	1.4	N.S.
Subjects within Sex	1.447	16	0.091	4.1	
Cigarettes	0.527	2	0.264	12.0	****
Cigarettes x Sex	0.002	2	0.010	0.4	N.S.
Residual	0.704	32	0.022		

(iii) RATIOS

L245/L246	L245/L247	L246/L247
1.27****	1.13*	0.88*

Estimated standard error of ratio = 0.05. Paired comparisons by Scheffé's test.

36.0

TABLE 16

ESTIMATED CO UPTAKE FROM DUPLICATION (mg)

(i) DATA

	L245	L246	L247	
FEMALES	9.6	19.8	15.8	15.1
	18.4	31.1	21.5	23.7
	12.6	21.4	11.5	15.2
	20.2	23.6	22.0	21.9
	18.4	27.2	22.0	22.5
	11.9	25.8	21.8	19.8
	15.0	20.1	15.9	17.0
	18.3	19.7	15.7	17.9
	14.2	26.0	18.8	19.7
MALES	22.7	29.2	26.0	26.0
	16.5	25.2	19.2	20.3
	13.1	18.2	19.9	17.1
	17.4	20.6	19.3	19.1
	16.7	31.2	22.7	23.5
	12.9	17.7	13.9	14.8
	17.2	23.2	28.1	22.8
	17.2	23.5	19.2	20.0
	17.6	26.4	11.1	18.4
	16.1	23.9	19.4	19.8

(ii) ANALYSIS OF VARIANCE TABLE (log transformed data)

Source	SS	DF	MS	F	P
Sex	0.066	1	0.066	0.8	N.S.
Subjects within Sex	1.393	16	0.087		
Cigarettes	1.442	2	0.721	36.0	****
Cigarettes x Sex	0.036	2	0.018	0.9	N.S.
Residual	0.642	32	0.020		

(iii) RATIOS

L245/L246	L245/L247	L246/L247
0.67****	0.83***	1.24****

Estimated standard error of ratios 0.05. Paired comparisons by Scheffé's test.

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TABLE 17

CARRY OVER BRAND EFFECTS

Parameter	L245/L246	L245/L247	L246/L247	Estimated Standard Error of Ratio
Total interval	1.03*	1.01	0.98	0.013
Mean interval	1.04	1.01	0.98	0.027
Total duration	1.00	0.99	0.99	0.023
Mean duration	1.00	0.99	0.99	0.018
Proportion puff time	0.97	0.98	1.01	0.029
Puff number	1.01	1.00	1.00	0.019
Butt length	0.99	1.00	1.01	0.009
Lit pressure drop	0.99	1.00	1.01	0.025
Total volume	0.99	0.99	1.00	0.024
Mean volume	0.99	0.99	1.00	0.016
Intensity	0.99	1.01	1.01	0.014

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TABLE 18

DIFFERENCES BETWEEN THE SEXES

Parameter	Ratio Male/Female	95% Confidence Interval for Ratio
Total interval	0.98	(0.82, 1.17)
Mean interval	1.04	(0.75, 1.38)
Total duration	1.06	(0.84, 1.34)
Mean duration	1.12	(0.89, 1.41)
Proportion puff time	1.08	(0.78, 1.50)
Puff number	0.95	(0.80, 1.12)
Butt length	0.95	(0.83, 1.10)
Lit pressure drop	1.02	(0.82, 1.27)
Total volume	1.07	(0.94, 1.23)
Mean volume	1.13	(0.95, 1.35)
Intensity	1.01	(0.82, 1.25)
TPM uptake	1.12	(0.92, 1.36)
Nicotine uptake	1.10	(0.93, 1.31)
CO uptake	1.07	(0.90, 1.27)

Parameter	Difference Male/Female	95% Confidence Interval for Difference
Slope at zero of cumulative puff volume function	6.2	(-2.8, 15.3)
Curvature of cumulative puff volume function	1.1	(-6.1, 8.3)

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TABLE 19

TRENDS OVER THE EXPERIMENT

Parameter	Rate of Increase (% per session)	95% Confidence Interval
Total interval	+0.1	(-0.3, 0.5)
Mean interval	-0.2	(-0.8, 0.4)
Total duration	+0.5*	(-0.1, 1.0)
Mean duration	+0.1	(-0.3, 0.6)
Proportion puff time	+0.3	(-0.3, 0.9)
Puff number	+0.3	(-0.1, 0.8)
Butt length	-0.0	(-0.2, +0.2)
Lit pressure drop	-0.5***	(-0.8, -0.2)
Total volume	-0.1	(-0.6, 0.5)
Mean volume	-0.4*	(-0.8, 0.0)
Intensity	-0.5***	(-0.9, -0.2)

CUMULATIVE PUFF VOLUMES