TECHNICAL REPORT

ISO/TR 19478-2

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ISO and Health Canada intense smoking parameters —

Part 2: Examination of factors contributing to variability in the routine measurement of TPM, water and NFDPM smoke yields of cigarettes

Paramètres de fumage ISO et Santé Canada Intense —

Partie 2: Examen des facteurs contribuant à la variabilité des mesures de routine de MPT, d'eau et de MPAEN dans la fumée de cigarette

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Foreword

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 126, *Tobacco and tobacco products*.

ISO/TR 19478 consists of the following parts, under the general title *ISO and Health Canada intense smoking parameters*:

— *Part 1: Results of an international machine smoking study*

— *Part 2: Examination of factors contributing to variability in the routine measurement of TPM, water and NFDPM smoke yields of cigarettes*

Introduction

ISO/TC 126 Working Group 10 (WG 10) was established by ISO/TC 126 in 2007 in response to a New Work Item Proposal by the British Standards Institution (BSI) for the development of a new regime for the machine smoking of cigarettes that was more intense than the then current ISO 3308:2000, and a subsequent questionnaire sent to TC 126 members. Twenty out of 26 members of ISO/TC 126 voted in favour of the following option:

"*to install a Working Group 10 dealing with an 'Intense Smoking Regime' which shall start with the preparatory work. WHO is invited to participate with their technical experts. No draft Standard is expected to be presented by this group until the future method proposal of WHO has been taken into consideration*".

The third session of the Conference of the Parties (COP) to the World Health Organization (WHO) Framework Convention on Tobacco Control Durban, South Africa, 17 to 22 November 2008, requested the Convention Secretariat to invite the WHO's Tobacco Free Initiative (TFI) to undertake the following task:

"*validate, within five years, the analytical chemical methods for testing and measuring the cigarette contents and emissions identified as priorities in the progress report of the working group 1 using the two smoking regimens set out in paragraph 18 of that report, and inform the Conference of the Parties through the Convention Secretariat on a regular basis of the progress made.*"

The two smoking regimens were specified in paragraph 18 of the report of the COP working group (FCTC/COP/3/6) as follows:

Smoking regimen	Puff volume (ml)	Puff frequency	Ventilation holes
ISO 3308:2000, Routine analytical cigarette-smoking machine — Definitions and standard conditions	35	Once every 60 s	No modifications
Same as ISO 3308:2000 but modified as indicated.	55	Once every 30 s	All ventilation holes must be blocked with Mylar adhesive tape.

The two regimes were those specified in ISO 3308 and by Health Canada in Method T-115. At the early meetings of WG 10, some new human smoking studies were presented and are included in Annex A for completeness of reporting, but WG 10 never considered the correlation with machine smoking regimes in detail as this brief had previously been given to ISO/TC 126/WG 9 and WG 9 had produced a comprehensive report, ISO/TR 17219:2013.

The WHO TFI requested the WHO Tobacco Laboratory Network (TobLabNet) to carry out the practical work of validating the two smoking regimes. In 2008, TobLabNet organized and carried out a collaborative test to measure the tar, nicotine and carbon monoxide yields of cigarettes when using the Health Canada Intense (HCI) regime. The collaborative test involved 14 laboratories smoking five products (three reference cigarettes/monitor test pieces and two commercial products). Details of this collaborative were supplied to ISO/TC 126/WG 10.

WG 10 had expressed a willingness from its inception to participate with the WHO groups in the development of an intense smoking regime but had not been invited to do so. It, therefore, decided at its fifth meeting in December 2009 to undertake a collaborative study to measure the tar, nicotine and carbon monoxide yields of cigarettes using both the ISO 3308:2000 and Health Canada intense smoking regimes. A steering group was established and the laboratory work was carried out in 2010 involving 35 laboratories smoking 10 products (eight commercial and two reference cigarettes/monitor test piece). A final report on the study was approved by WG 10 and subsequently converted to a Technical Report, ISO/TR 19478-1. ISO/TR 19478-1 provided a basic analysis of the study data, drawing conclusions about the possible sources of the increased variability associated with the HCI regime.

These conclusions provided the basis for the additional studies reported here and instigated to provide a more complete understanding of how the smoke yield changes with increasing smoking intensity.

ISO and Health Canada intense smoking parameters —

Part 2:
Examination of factors contributing to variability in the routine measurement of TPM, water and NFDPM smoke yields of cigarettes

1 Scope

This part of ISO/TR 19478 extends the analysis reported in ISO/TR 19478-1:2014 and reports additional studies focused on the conclusions i) and j) from that Technical Report. It identifies and assesses factors impacting on the measurement of smoke TPM, NFDPM, nicotine, water, and carbon monoxide yields when increasing the intensity of the puffing regime from that specified in ISO 3308:2000 to the regime specified in Health Canada Method T-115.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
cigarette coal
carbonised burning tip of a tobacco rod

2.2
ISO regime
puffing regime when taking one puff of 35 ml volume and 2 s duration every 60 s as defined in ISO 3308:2000

2.3
Health Canada Intense regime
HCI regime
puffing regime, first described by Health Canada, when taking one puff of 55 ml volume and 2 s duration every 30 s with 100 % of the ventilation zone on the cigarette filter blocked

2.4
linear (smoking) machine
smoking machine complying with the requirements of ISO 3308:2000 with each cigarette holder directly coupled to a CFH (smoke trap)

Note 1 to entry: The CFH is coupled via a port to its own suction mechanism and held in a fixed position while each cigarette is smoked. The most common configuration has 20 ports in line.

2.5
rotary (smoking) machine
smoking machine complying with the requirements of ISO 3308:2000 with each cigarette holder coupled sequentially via a port to a single CFH (smoke trap) and suction mechanism

Note 1 to entry: The most common configuration has 20 ports on a carousel sharing a single CFH and suction mechanism.

2.6
Massachussetts regime
MA regime
puffing regime, used in Massachusetts, USA, when taking one puff of 45 ml volume and 2 s duration every 30 s with 50 % of the ventilation zone on the cigarette filter blocked

2.7
option B regime
puffing regime proposed by ISO/TC 126 Working Group 9 when taking one puff of 60 ml volume and 2 s duration every 30 s with 50 % of the ventilation zone on the cigarette filter blocked

3 Abbreviated terms

CFH	Cambridge Filter Holder
CFP	Cambridge Filter Pad
COP	Conference of the Parties to the World Health Organization Framework Convention on Tobacco Control
NFDPM or tar	Nicotine Free Dry Particulate Matter
TNCO	tar, nicotine and carbon monoxide where tar is specifically nicotine free dry particulate matter (NFDPM)
TPM	total particulate matter
RH	relative humidity
SVD	Saturated Vapour Density
TobLabNet	World Health Organization Tobacco Laboratory Network
WHO	World Health Organization
ΔT	Reduction in the time to smoke a cigarette due to puffing, calculated as: (Time to smoulder burn the cigarette) - (Time to burn the cigarette when puffing)

4 Principle

Following the analysis of the data from the TNCO study (ISO/TR 19478-1), WG 10 decided to review the impact of increasing puffing intensity on the measurement of TPM, NFDPM, nicotine, water and carbon monoxide yields from cigarettes with particular emphasis on differences resulting from the use of rotary or linear smoking machines. The Ad Hoc Group (AHG) of WG 10 was set up to give focus to the review process. The membership of the AHG necessarily included representatives of the manufacturers of smoking machines as well as those WG 10 members who wished to be actively involved in further studies. The review was carried out with particular reference to the conclusions from the WG 10 TNCO study which compared smoke yield data for the ISO regime, as specified in ISO 3308:2000 and ISO 4387, with that for the HCI regime, as specified in the Health Canada Method T-115. The AHG first identified a number of differences in design features between rotary and linear machines with the potential to alter the collection of smoke condensate and so increase the variation in smoke yield measurements. Individual AHG members then used their expertise to create protocols to evaluate these factors in their respective laboratories.

Conclusions i) and j) of ISO/TR 19478-1:2014 provided the focus for the work of the AHG, although other issues were also considered. Clauses 5 and 6 provide a summary of the understanding developed within WG 10 and the AHG of the issues identified in conclusions i) and j).

The studies providing the background to this part of ISO/TR 19478 are listed in Annex A together with a summary of the content of each and the meeting at which they were presented. Annex B provides a list of all meetings of WG 10 and the Ad Hoc Group of WG 10 until the end of 2013.

5 The influence of smoking intensity on the yield and composition of cigarette smoke

5.1 General

The results of the collaborative study described in ISO/TR 19478-1 had shown the reproducibility of the NFDPM yield measurements from 10 products collected under the HCI smoking regime and measured in many laboratories, were worse than when using the ISO regime. This finding was supported by other collaborative studies run by the WHO TobLabNet and by CORESTA[1] as summarized in A.11. The range of products to which this conclusion can be applied was widened to include products of 16 mm to 18 mm in circumference (super slims) in a further small study (A.20). The ISO WG 10 TNCO study data set has also been used to discuss the problems with statistical outlier analysis when combining data from rotary and linear machines which give different measured water yields.[2][3]

Apart from the increased puff volume and frequency specified for the HCI regime, it is also necessary to block 100 % of the ventilation on the cigarette filter. The Health Canada Method T-115 specifies overwrapping the filter with "invisible" tape (adhesive cellophane tape) to block the ventilation holes in the cigarette filter but special cigarette holders have also been developed to achieve the same outcome. The overwrapping of filters with adhesive tape was investigated (A.19) to eliminate it as a potential cause of the increased measurement variability and another study (A.15) showed that taping and using specially designed vent blocking cigarette holders gave similar yields.

In order that the increased yield resulting from the much increased smoking intensity of the HCI regime does not overload the CFP when using a linear machine with the 44 mm CFP (ISO 4387 specifies a maximum load of 150 mg), three cigarettes are smoked per smoking run rather than five. Another study (A.23) confirmed the 150 mg limit for the ISO regime but found it could be doubled when using the HCI regime.

5.2 A review of information relevant to conclusion i) of ISO/TR 19478-1:2014

Conclusion i) stated,

"As expected from previous studies, the water yields were disproportionately higher than other measured smoke parameters under the HCI regime. This water effect is a contributory factor to the increases in R values, but the magnitude of its contribution is uncertain."

Conclusion i) set the need to better understand how the smoke yield changed with smoking intensity, both in magnitude and composition. In particular, to investigate the cause of greatly increased smoke water content.

It can be seen (Table 1) from the TPM and water yields for the 10 products tested in the WG 10 study that there is a consistency to the proportions of nicotine and water in the TPM for all 10 products and both smoking regimes. The most important feature of the data is the increase in the average water yield from approximately 10 % of the TPM for the ISO regime to almost 30 % for the HCI regime. It is by far the most abundant component of the TPM with nicotine being only 5 % of the TPM for the HCI regime. This finding signals a potential measurement problem using the normal ISO procedures for TPM and water measurement as the collection system, the CFP held in the CFH, is specifically designed for collecting particulate material. If a major proportion of the smoke water is in the vapour phase, the collection efficiency of the CFP/CFH unit will be compromised, as will the subsequent measurement of the smoke water yield.

Table 1 — TPM, water and nicotine yields under the ISO and HCI smoking regime

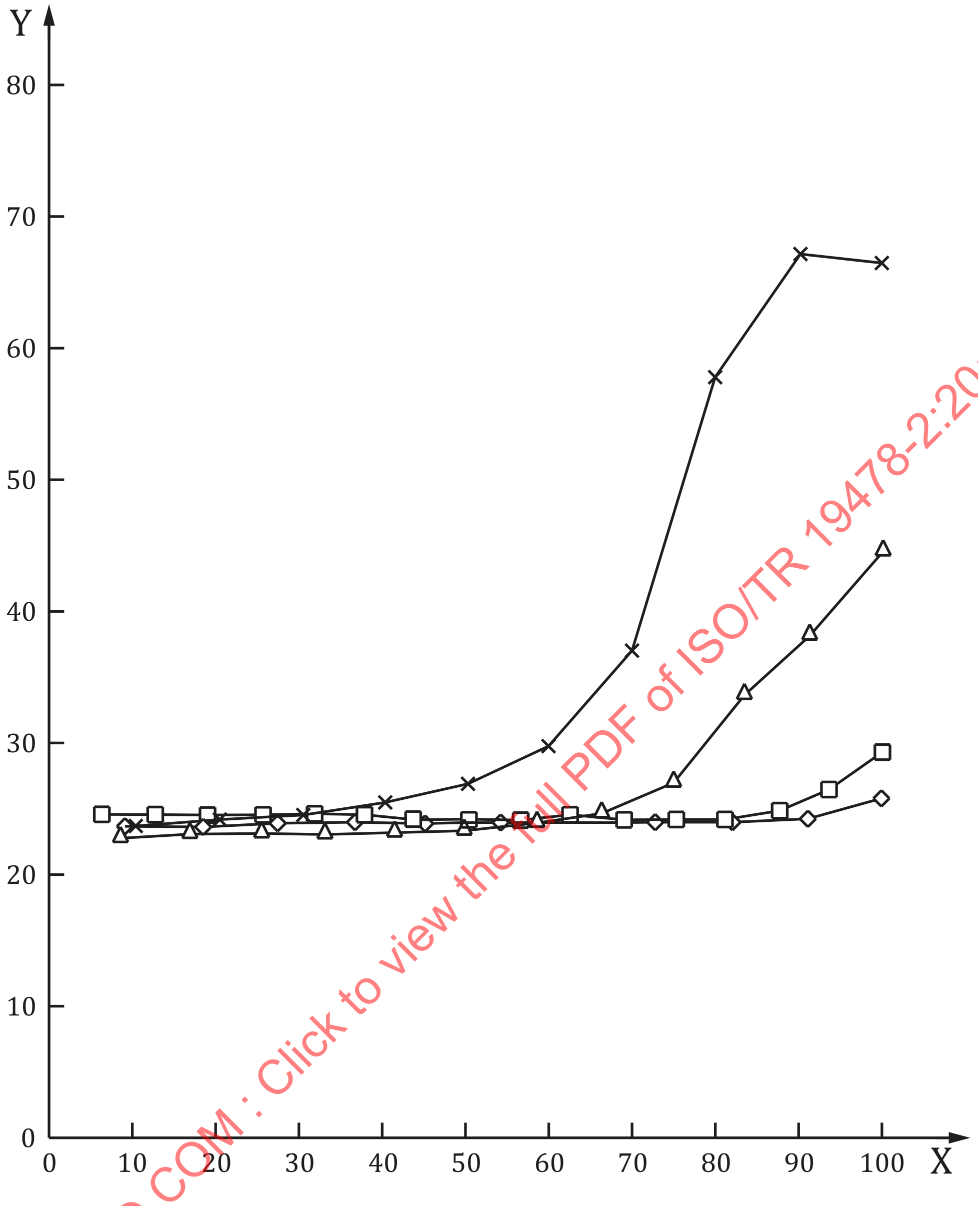
Product code	ISO regime					HCI regime				
	TPM	Water		Nicotine		TPM	Water		Nicotine	
	mg/cig	mg/cig	% of TPM	mg/cig	% of TPM	mg/cig	mg/cig	% of TPM	mg/cig	% of TPM
A	1,28	0,10	7,5	0,11	8,4	25,41	7,35	28,9	1,27	5,0
B	5,21	0,40	7,6	0,39	7,5	31,26	9,39	30,0	1,34	4,3
C	10,81	1,26	11,6	0,68	6,3	39,84	11,87	29,8	1,79	4,5
D	10,03	0,93	9,2	0,82	8,1	39,07	11,19	28,6	2,11	5,4
E	11,54	1,10	9,5	0,66	5,7	29,71	6,06	20,4	1,41	4,7
F	10,65	1,12	10,5	0,75	7,1	43,69	13,42	30,7	2,07	4,7
G	12,05	1,51	12,5	0,83	6,9	43,43	14,16	32,6	2,09	4,8
H	11,08	1,06	9,6	0,67	6,0	40,09	11,47	28,6	1,68	4,2
I	2,08	0,19	9,1	0,15	7,4	27,05	9,03	33,4	0,99	3,7
J	17,30	1,69	9,7	1,37	7,9	41,18	10,11	24,5	2,68	6,5
Mean	**9,20**	**0,93**	**9,7**	**0,64**	**7,1**	**36,07**	**10,40**	**28,8**	**1,74**	**4,8**

The understanding of subsequent subclauses will be aided by an understanding of the nature of cigarette smoke and the formation process in the burning tobacco rod. After lighting, the tobacco rod forms the coal, a carbonised section at its tip, which then promotes the continuous burning of the remaining tobacco through the heat liberated from the oxidation of the carbon. Studies[4] have established thermal profiles in the region of the cigarette coal which show that the temperature at the char line on the cigarette paper is approximately 450 °C with the tobacco temperature rapidly dropping to about 300 °C within 3 mm to 4 mm. The tobacco in this region is denuded of volatile components which evaporate and migrate along the tobacco rod away from the hot coal. They then cool with some condensing to form a smoke aerosol in equilibrium with the remaining vapour cloud. At the same time, some smoke components will condense onto the tobacco as well as diffusing through the cigarette paper to be lost to the surrounding environment.

During puffing, volatile compounds are transferred and deposited further along the tobacco rod. This deposited material is partly lost by diffusion through the cigarette paper between puffs with the remaining material accumulating with successive puffs until the char line reaches it. If this occurs during a puff, the material becomes part of the smoke yield from that puff so increasing the yield from the puff. This transfer process has been demonstrated by following changes in the density of the tobacco rod during smoking.[5]

5.3 Puff by puff smoke temperature measurements

The first of a number of relevant studies (A.4) presented to WG 10 provided temperature data for individual puffs as a cigarette was smoked. The data was for peak temperatures at two positions in the cigarette filter and for four puffing regimes, ISO, HCI, MA and Option B from the report of ISO/TC 126/WG 9 (ISO/TR 17219:2013) The temperatures measured 5 mm from the mouth end of the filter of a 1 mg tar cigarette (ISO) are shown in Figure 1.



Key

X proportion of cigarette burnt (%)

Y maximum temperature in filter (°C)

ISO regime

MA regime

WG 9 (B) regime

HCI regime

Figure 1 — Temperatures 5 mm from mouth end of cigarette filter (A.4)

Figure 1 shows that the temperature of the smoke as it leaves the cigarette filter is near the ambient temperature of 22 °C for the early puffs. This indicates the heat exchange with the tobacco and filter material, together with mixing with air drawn into the cigarette through the cigarette paper and filter, is sufficient to cool the smoke to the temperature of the test environment.

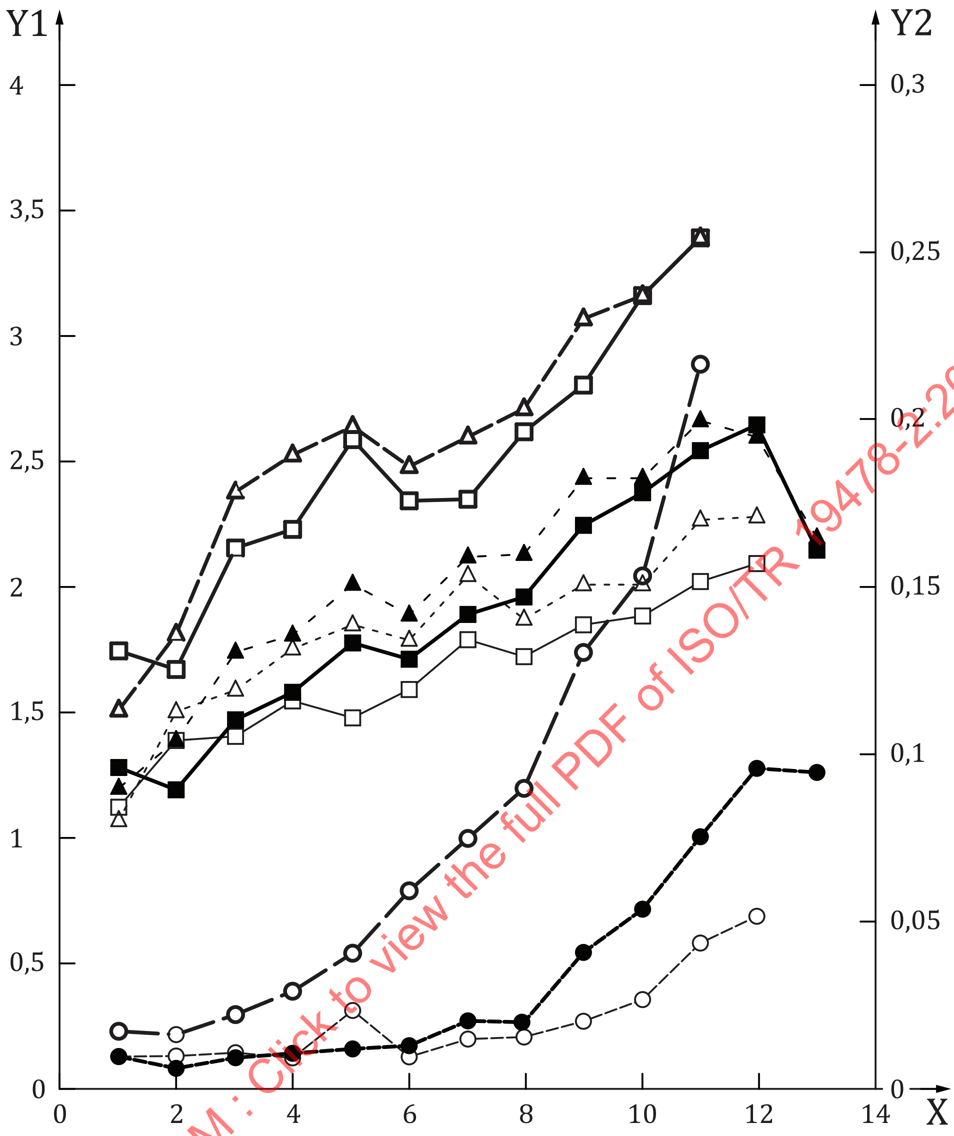
As further puffs are taken and the tobacco rod burns down, the temperature rises above 22 °C. The more intense the smoking regime, the earlier this occurs during the smoking process and the greater is the increase in temperature above the ambient level.

These temperature measurements are highly significant when considering the formation of the smoke aerosol. Smoke is initially formed as a complex mixture of hot vapours and gases just behind the cigarette coal. It then becomes an aerosol as it is drawn through the tobacco rod and cools. The partitioning of compounds between the vapour and particulate phases will continue to change until it reaches a fixed temperature. Since the collection and measuring system is held at 22 °C, it is desirable for the smoke to leave the cigarette at this temperature to prevent further changes during collection. This will not happen when using very intense smoking regimes since the temperature measurements in Figure 1 indicate that the smoke from the later puffs is considerably above 22 °C.

5.4 Puff by puff smoke yields

It has been shown that the temperature of smoke leaving a cigarette can be above the ambient temperature for the later puffs, particularly when the intensity of the smoking regime is increased. As the formation of smoke from a vapour cloud behind the cigarette coal is primarily driven by the temperature change, it seems probable that the smoke composition will also change during the smoking of a cigarette. A change in smoke composition linked to its exit temperature from the cigarette should be apparent from reviewing the puff by puff smoke yield. Suitable single puff yield data[7] was made available to the Ad Hoc Group. The smoke yield measurements were for the 1R4F reference cigarette using a smoking regime with puffs of 60 ml volume and 2 s duration being taken every 30 s. The level of ventilation at the cigarette filter was also varied by blocking 0 %, 50 % or 100 % of the ventilation holes.

The NFDPM, nicotine and water yields for individual puffs are given in Figure 2. The data in Figure 2 show that the yields of the three smoke components increase both as the cigarette is consumed during smoking and also as a greater proportion of the filter ventilation holes are blocked. The general increase in smoke yield as the tobacco rod is burnt is expected and due to reduced filtration and ventilation in the shorter tobacco rod. The rate of increase in yield for NFDPM and nicotine is similar for successive puffs and for each of the three levels of vent blocking. The water yields show a distinctly different pattern with the rate of increase being much greater as the cigarette is consumed, and the rate is much increased as a greater percentage of the vents are blocked.



Key

X puff number

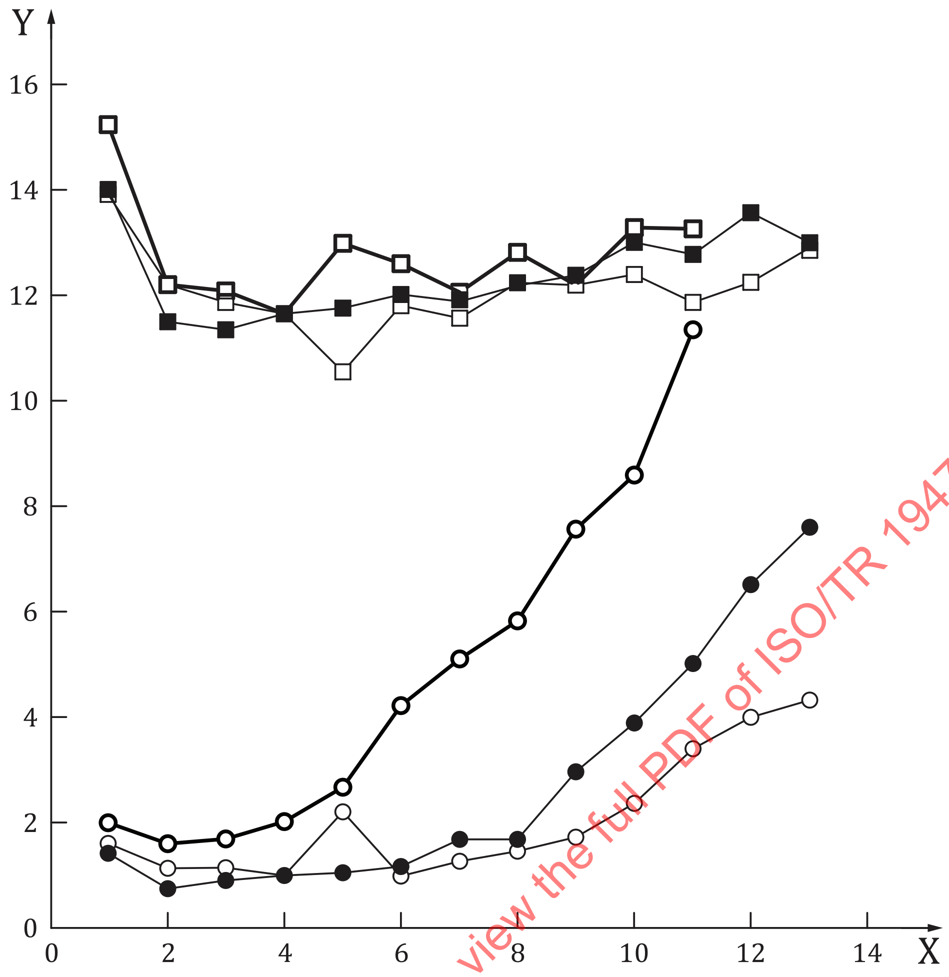
Y1 NFDPM and water yield (mg/puff)

Y2 nicotine yield (mg/puff)

- NFDPM-0 % VB
- water-0 % VB
- nicotine-0 % VB
- NF DPM-50 % VB
- water-50 % VB
- nicotine-50 % VB
- NF DPM-100 % VB
- water-100 % VB
- nicotine-100 % VB

Figure 2 — Puff by puff yields from 1R4F reference cigarette[7]

These patterns of change are more clearly shown by taking the ratio of the NFDPM and water yields to those for nicotine as shown in Figure 3.



Key

X puff number

Y yield as a ratio to nicotine

water-0 % VB

NFDPM-0 % VB

water-50 % VB

NF DPM-50 % VB

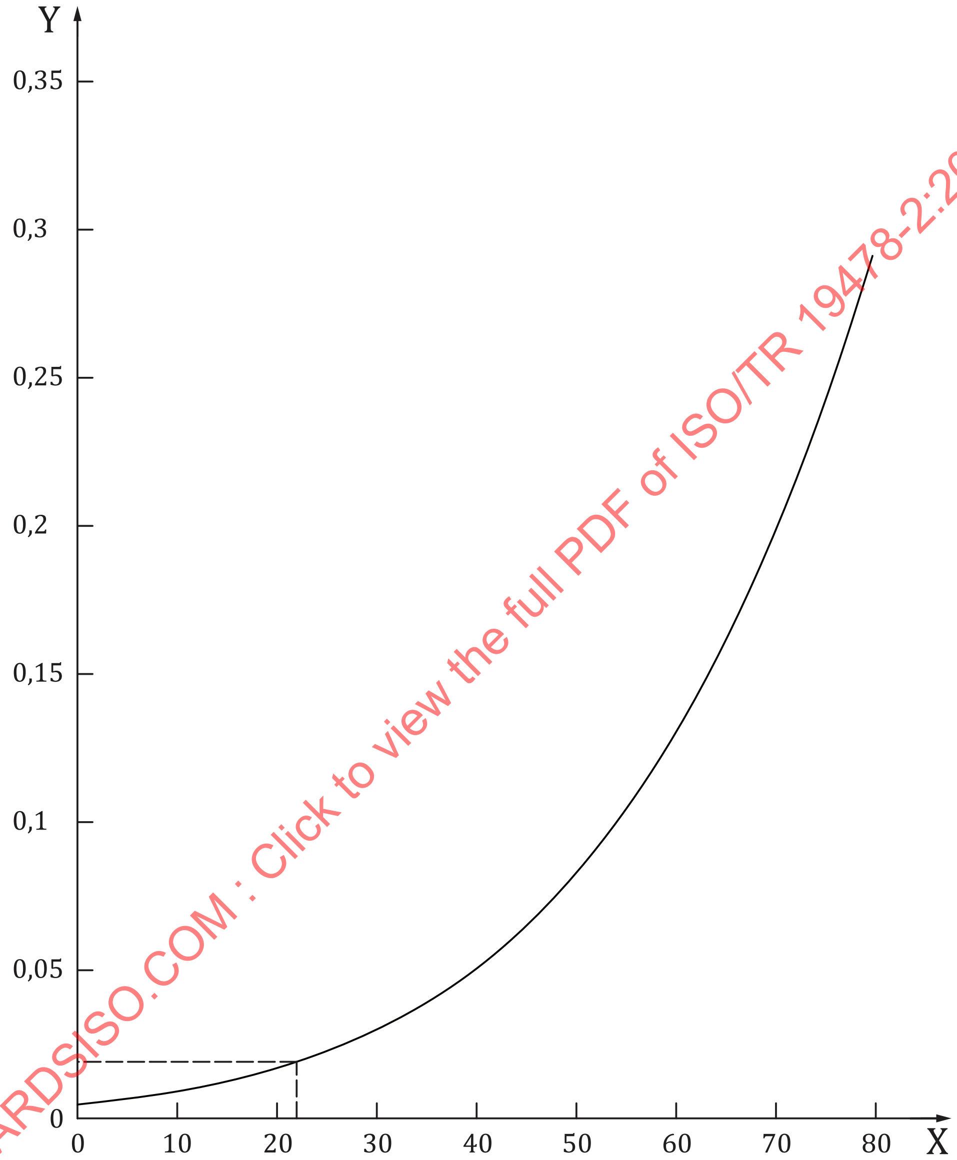
water-100 % VB

NF DPM-100 % VB

Figure 3 — Puff by puff yields of NFDPM and water as a ratio to nicotine yield[7]

The NFDPM to nicotine ratios in Figure 3 show that the relative yield of these smoke components is little changed during the smoking of a cigarette or by decreasing the filter ventilation. In contrast, the water to nicotine ratios show that water yields are relatively unchanged for the initial puffs but then increase rapidly. The water yield also increases as the filter ventilation is reduced by vent blocking.

The puff by puff water yields cannot be directly correlated with the temperature measurements in 5.3 as the cigarettes tested were not of the same design, but a mechanism to link the increased smoke water content with an increase smoke temperature can be proposed. Tobacco naturally absorbs water from the environment to a level of approximately 10 % by weight when stored at a temperature of 22 °C and a 60 % relative humidity. When a cigarette is lit, the heat from the coal drives a cloud of volatile tobacco components down the tobacco rod where they cool and condense to form the smoke aerosol. Water vapour will be the biggest vapour phase smoke component due to the release of the water absorbed by tobacco and the additional amount produced as a combustion product. Previously unpublished work (A.9) measured 200 mg to 300 mg of water per cigarette in the sidestream smoke from 84 mm long filter cigarettes. With such large amounts of water present when smoke is generated, it seems inevitable that the concentration will remain high, at or near the saturated vapour density (SVD) of water, as it cools continuously while travelling through the tobacco rod. Increasing puffing intensity will increase the heat transfer from the cigarette coal into the tobacco rod as well as reducing the residence time of the smoke. As a consequence, the smoke will cool to a lesser extent and leave the cigarette at a higher temperature. As shown in Figure 4, the SVD increases at a much greater rate than the temperature so allowing the smoke to carry much greater quantities of vapour phase water.



Key

X temperature °C

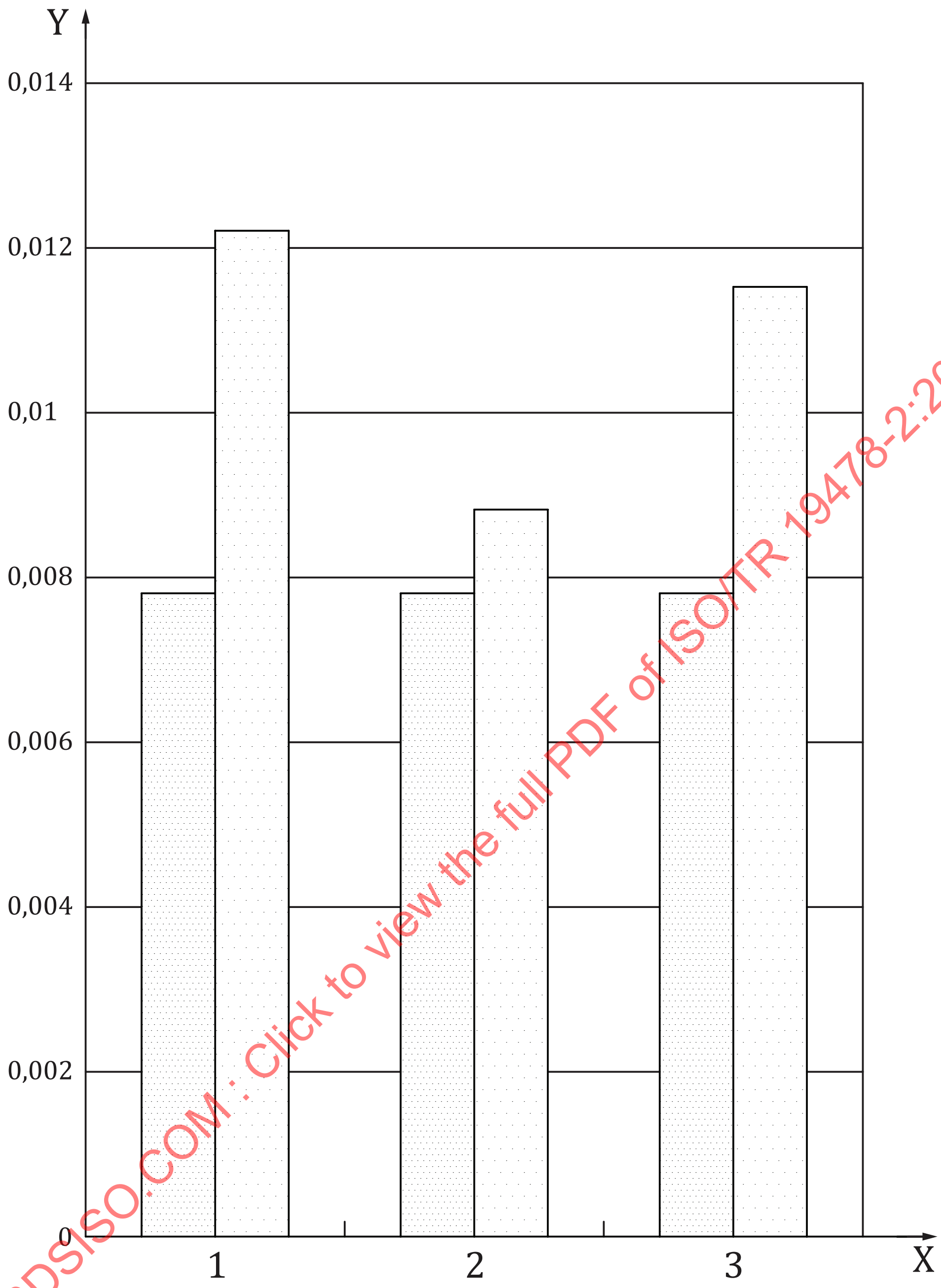
Y saturated vapour density mg/ml

NOTE SVD at 22 °C = 0,0194 mg/ml.

Figure 4 — Change in the saturated vapour density of water with temperature

Although the temperature data from 5.3 cannot be directly correlated with the puff by puff yields discussed in this clause, it is of interest to calculate the temperatures necessary to produce the measured water yields in order to compare with those in 5.3. The relationship between temperature and SVD in Figure 4 can be used to convert the puff by puff water yields in Figure 2 to equivalent temperatures after the yields are converted to concentrations in mg/ml by dividing by the puff volume. When calculating the temperatures, it is assumed that the water vapour will always be present as a saturated vapour, i.e. the RH is 100 %. This assumption is made on the basis of there being a continuous drop in temperature along the tobacco rod and the cigarette filter before the smoke leaves the cigarette. The smoke temperature would then continue to fall as it passed through the CFH so that the smoke water would remain as a saturated vapour at the exit of the CFH.

Support for this assumption comes from the A.16 study which collected and measured the vapour phase water at the exit of the CFH using an impinger trap. The vapour phase water concentration is shown in Figure 5 for the three products tested using the HCI regime and a linear smoking machine. When making these measurements, it was assumed that the water content of the air drawn into the cigarette during puffing would contribute to the vapour phase water and needed to be subtracted to determine the true smoke yield. The A.16 study measurements were reported after subtracting the background moisture as determined from blank smokings of unlit cigarettes to the same puff number. Since the subtraction of the blank measurements effectively reduces the smoke measurements by an amount equivalent to 60 % RH at 22 °C, the remaining values will indicate the vapour phase water content to be saturated, i.e. 100 % RH, if equivalent to 40 % RH at 22 °C. The vapour density equivalent to 40 % RH at 22 °C is also indicated in Figure 5. It is evident that the vapour density of the water leaving the CFH was above the 40 % level for all three products indicating that it was still saturated. It was, therefore, above the SVD at 22 °C before subtracting the blank value and, since the smoke cannot carry water at a greater concentration than the SVD, the temperature of the smoke must have been above 22 °C.



Key

1 3R4F

2 4 mg brand

3 1 mg brand

X test sample

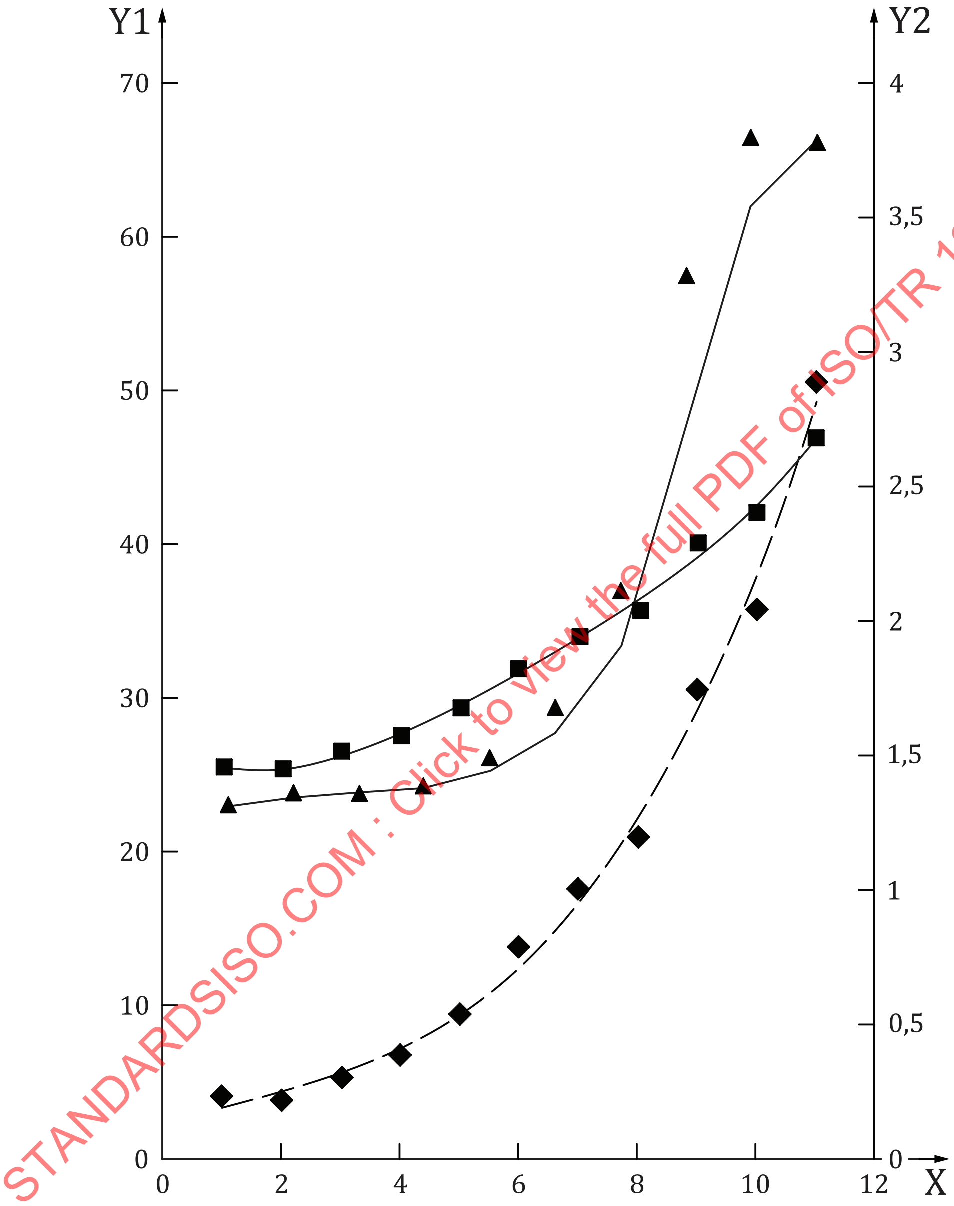
Y vapour density (mg/ml)

40 % of SVD at 22 °C

measured VD-ambient VD

Figure 5 — Water vapour density at exit of CFH from A.16 study data (linear smoking machine)

The equivalent temperatures to produce a vapour phase water content equal to the per puff yields in Figure 2 while also maintaining a saturated vapour density at the exit of the CFH at 22 °C are plotted in Figure 6. Also plotted in Figure 6 are the measured temperatures for the HCI regime from Figure 1 as well as the measured water yields from Figure 2. It is clear from the measured temperatures that the calculated temperature values could easily be achieved when smoking a cigarette. From this observation, it follows that the majority, and possibly all, of the rapid increase in the per puff water yield for the later puffs can be attributed to the increase in the smoke temperature and associated SVD, allowing the smoke to carry over a much increased quantity of water from the cigarette to the CFH. The agreement between the measured and calculated temperature values is surprisingly good even though the data is from different products, the measured temperatures are peak values rather than average and the contribution of the particulate phase water has not been taken into account. This is possibly an indication of the smoke temperature being the dominating factor in determining the water content of cigarette smoke.



Key

X puff number
Y1 temperature (°C)
Y2 water yield (mg/puff)
■ predicted temperature (°C)
▲ measured temperature* (°C)
◆ water (mg/puff)

Figure 6 — Measured (*A.4) and calculated puff by puff temperatures, and measured water yields

5.5 Smoking intensity and cigarette smoke yields

Although studies have been carried out to determine how smoke yields change with the smoking regime used to measure them, they have predominantly been to directly compare the ISO regime with alternative regimes proposed by public health bodies. Very few studies have been designed to make possible the development of predictive models by tracking the change in smoke yields over a wide range of smoking intensities.

The smoke yield data in Table 2 for 16 smoking regimes from a study (A.9) carried out in the 1980s, hereafter called the 1980s study was re-analysed before presentation to WG 10. The data was produced using a four port linear smoking machine with each determination based on smoking two channels of five cigarettes (i.e. 10 cigarettes).

Table 2 — Data for an unventilated 15 mg ISO king size brand from the 1980s study (A.9)

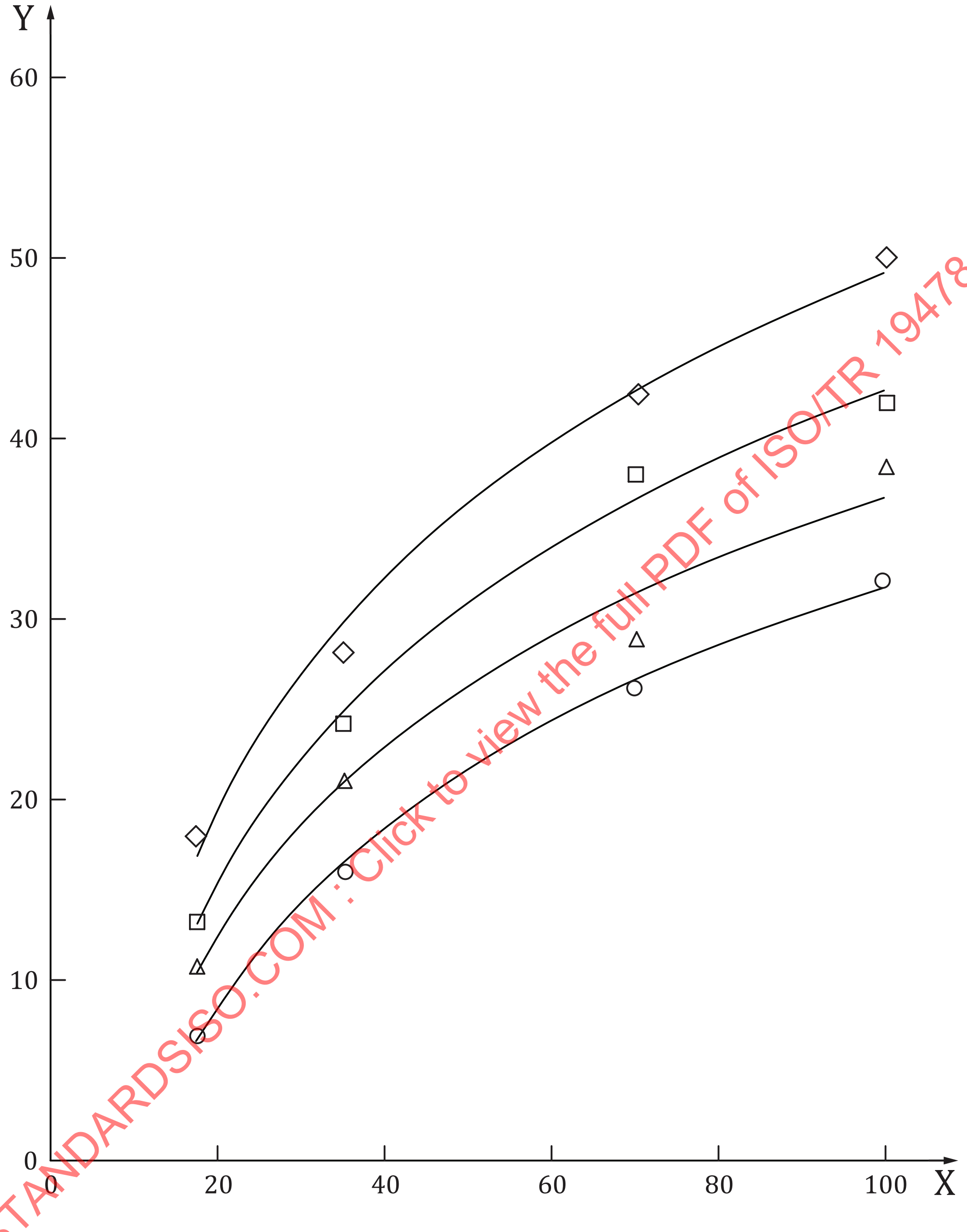
Puff volume	**Puff frequency** (puffs/min)	**1**	**1,5**	**2**	**3**
17,5 ml	Puff number	10,0	14,3	18,5	24,5
	NFDPM yield (mg/cig)	7,01	10,83	13,31	18,00
	Water yield (mg/cig)	0,22	0,44	0,66	0,52
	Nicotine yield (mg/cig)	0,78	1,07	1,33	0,95
	Filter retention (%)	49,0	49,0	49,6	—
35 ml	Puff number	9,1	11,9	14,4	19,6
	NFDPM yield (mg/cig)	16,01	21,28	24,28	28,21
	Water yield (mg/cig)	1,34	2,30	3,72	5,62
	Nicotine yield (mg/cig)	1,46	1,95	2,27	2,52
	Filter retention (%)	40,3	42,1	42,3	43,1
70 ml	Puff number	7,3	9,7	11,2	12,6
	NFDPM yield (mg/cig)	25,98	31,96	38,07	42,45
	Water yield (mg/cig)	7,56	14,02	19,70	28,64
	Nicotine yield (mg/cig)	2,20	2,68	3,30	3,59
	Filter retention (%)	36,1	37,5	36,5	36,6
100 ml	Puff number	6,3	8,6	9,7	11,0
	NFDPM yield (mg/cig)	32,58	38,60	41,96	50,07
	Water yield (mg/cig)	14,50	22,66	27,72	39,84
	Nicotine yield (mg/cig)	2,70	3,25	3,46	4,09
	Filter retention (%)	35,1	35	36,2	35,4

Table 3 — Product details for 2011 study (A.14)

Code	**L**	**LV (L with ventilation holes taped)**
ISO NFDPM (mg/cig)	3,3	7,9
Cigarette length (mm)	83	83
Butt length (mm)	35	35
Filter length (mm)	27	27
Filter ventilation (%)	49,3	0 (ventilation holes taped)

The puff duration for all regimes was held at 2 s. The study used three cigarette brands with nominal ISO NFDPM yields of 15 mg, 9 mm and 1 mg. The original purpose of the study was to investigate if the rank order of brands, based upon smoke yields, was fixed over a wide range of smoking regimes. The study did not find any change in ranking.

The data was originally reported with the puff volume and puff frequency as separate variables as shown in Figure 7 for the unventilated 15 mg ISO tar brand.



Key

X puff volume (ml)

Y NFDPM (mg/cig)

◇ 3 puffs/min

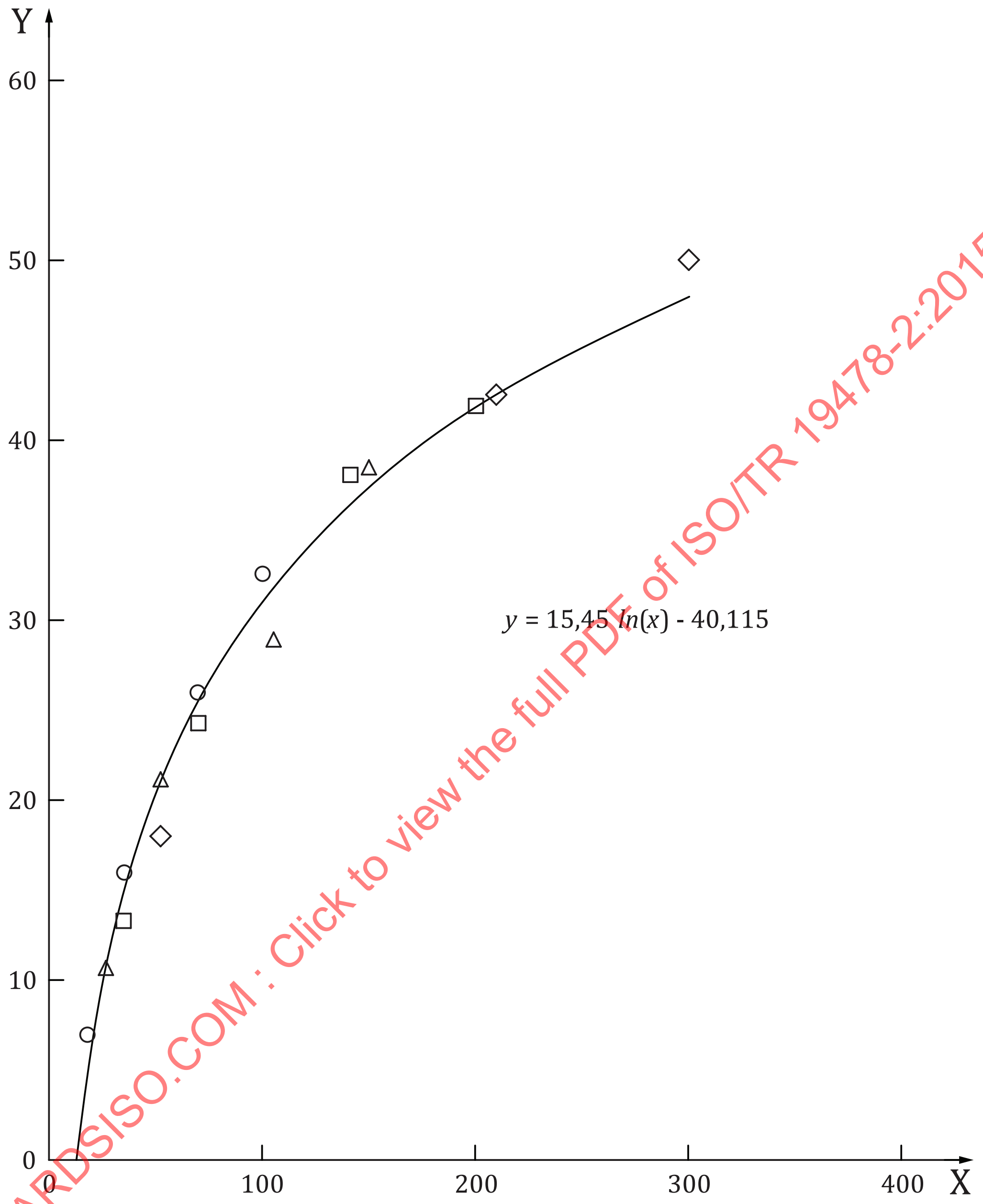
□ 2 puffs/min

△ 1,5 puffs/min

○ 1 puffs/min

Figure 7 — NFDPM yields for 15 mg ISO tar brand for all 16 smoking regimes from 1980s study (A.9)

The data was re-analysed and presented to WG 10 after creating a new variable defined as the puffing intensity (Ip) by taking the product of the puff volume and frequency. This variable is a measure of the volume of air drawn into the cigarette every minute due to puffing. The correlation with NFDPM yield is good, as shown by the trend line in Figure 8 for the 15 mg ISO tar brand.



Key

X puffing intensity (ml/min)

Y NFDPM (mg/cig)

◇ 3 puffs/min

□ 2 puffs/min

△ 1,5 puffs/min

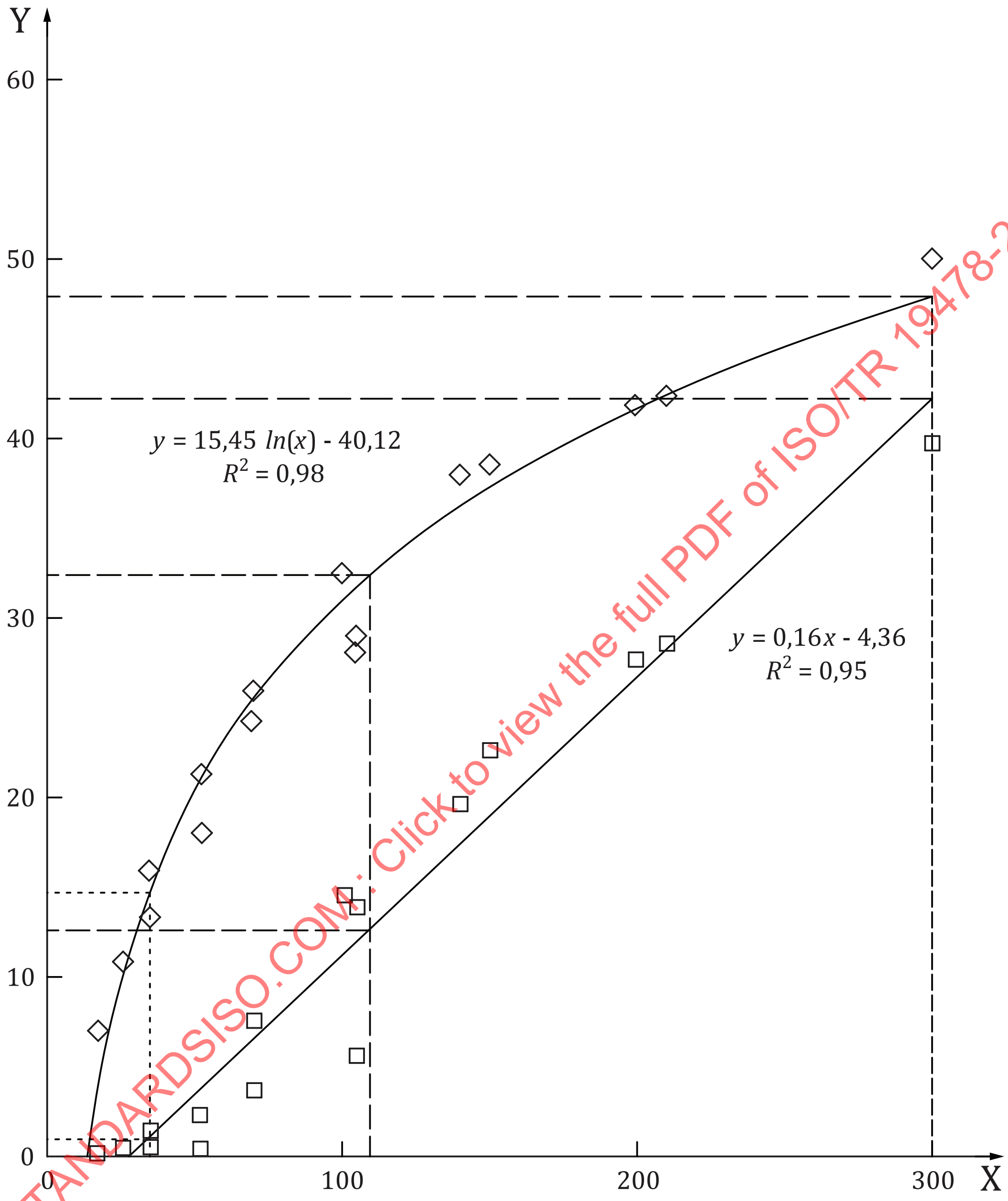
○ 1 puffs/min

Figure 8 — Puffing intensity versus NFDPM yield for 15 mg ISO tar brand from the 1980s study (A.9)

Although not shown, the same type of logarithmic relationship was found (A.9) between puffing intensity and the nicotine and carbon monoxide yields from this brand.

The relationship between the water yield and puffing intensity was very different as shown in Figure 9 for the 15 mg ISO tar brand. Relative to tar (NFDPM), the water yield increases from about 10 % at the

ISO puffing intensity to about 40 % at the HCI puffing intensity and climbs to about 90 % at 300 ml/min, the highest puffing intensity used. The relative yields of tar and water are similar to those found in the WG 10 TNCO study supporting the use of this data for general predictions. The data indicates that the use of an intense smoking regime, relative to the ISO regime, will result in a disproportionate increase in the yield of smoke water.



Key

X	puffing intensity (ml/min)	- - - - - - - -	ISO (35 ml/min)
Y	yield (mg/cig)	— — —	HCl (110 ml/min)
◇	NFDPM	—— ——	300 ml/min
□	water		

NOTE	*Ip*	ISO	HCI	300
	NFDPM/water	13,7	2,55	1,14

Figure 9 — Puffing Intensity versus NFDPM and water yield for 15 mg ISO tar brand from 1980s study (A.9)

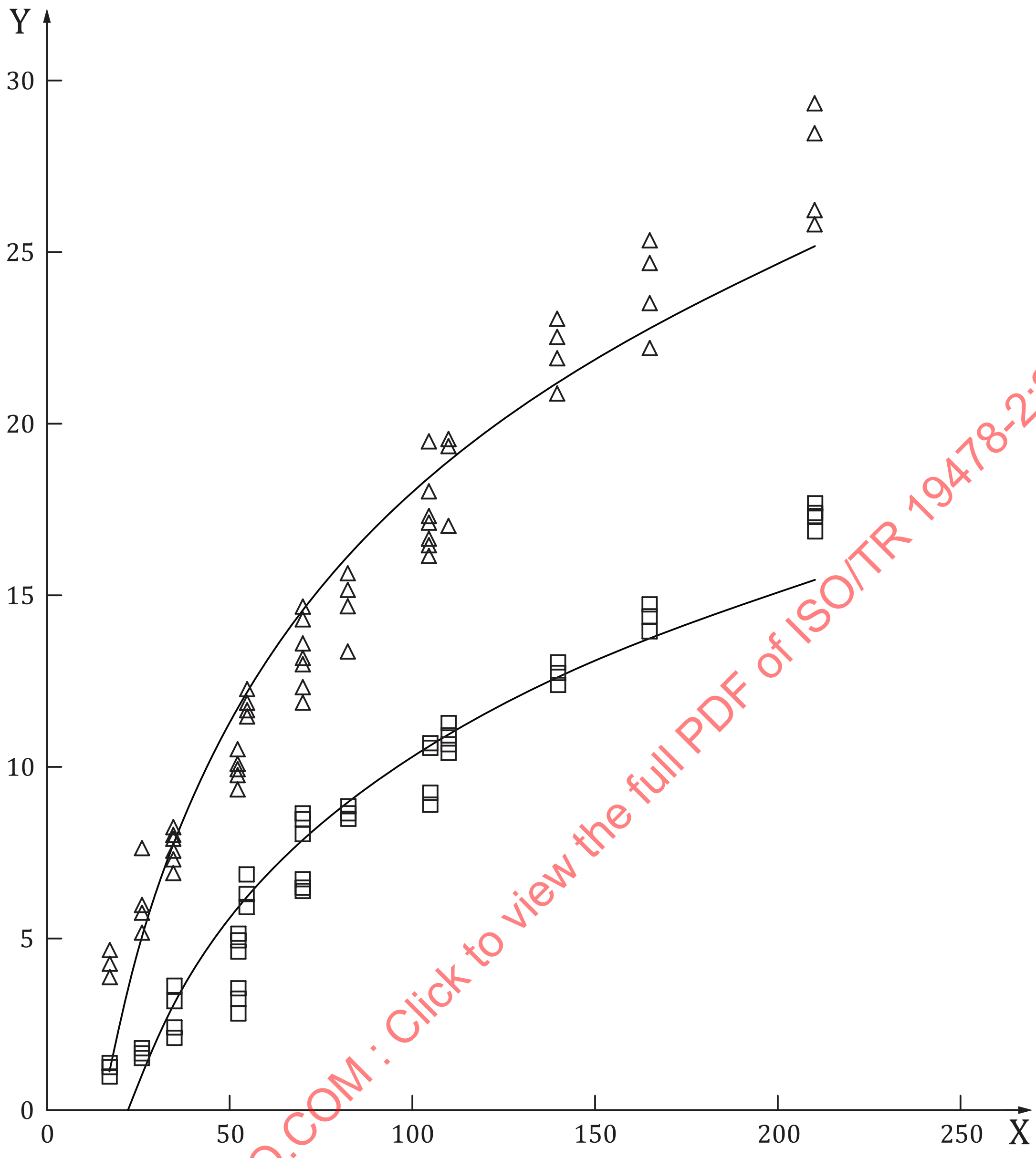
The trends found with the data from the 1980s study were supported by data (A.14) from a similar more recent study carried out in 2011 using two commercial products from that time.[8] These products had relatively lower yields, lower tobacco weight and an American blend rather than a Virginia style. As well as smoking the two products without modification, the product with filter ventilation was smoked with the ventilation holes taped to produce a third product with no filter ventilation. Only the measurements from the product smoked normally (L) and with the vents taped (LV) are considered in order to analyse the impact of vent blocking on smoke yields. The product details are given in Table 3.

The products were smoked using the smoking regimes in Table 4 with the puff duration held at 2 s for all regimes. All smoking runs were carried out on a linear smoking machine following ISO procedures apart from the set puffing regime.

Table 4 — Smoking regimes for 2011 study (A.14)

Puff volume (ml)	**Puff frequency** (puffs/min)			
17,5	1	1,5	2	3
35	1	1,5	2	3
55	1	1,5	2	3
70	1	1,5	2	3

Figure 10 shows the NFDPM yields plotted against the puffing intensity for the two products. The data best fits a logarithmic relationship in the same way as the data from the 1980s study. Figures 11 and 12 show the corresponding nicotine and carbon monoxide yields plotted against puffing intensity.



Key

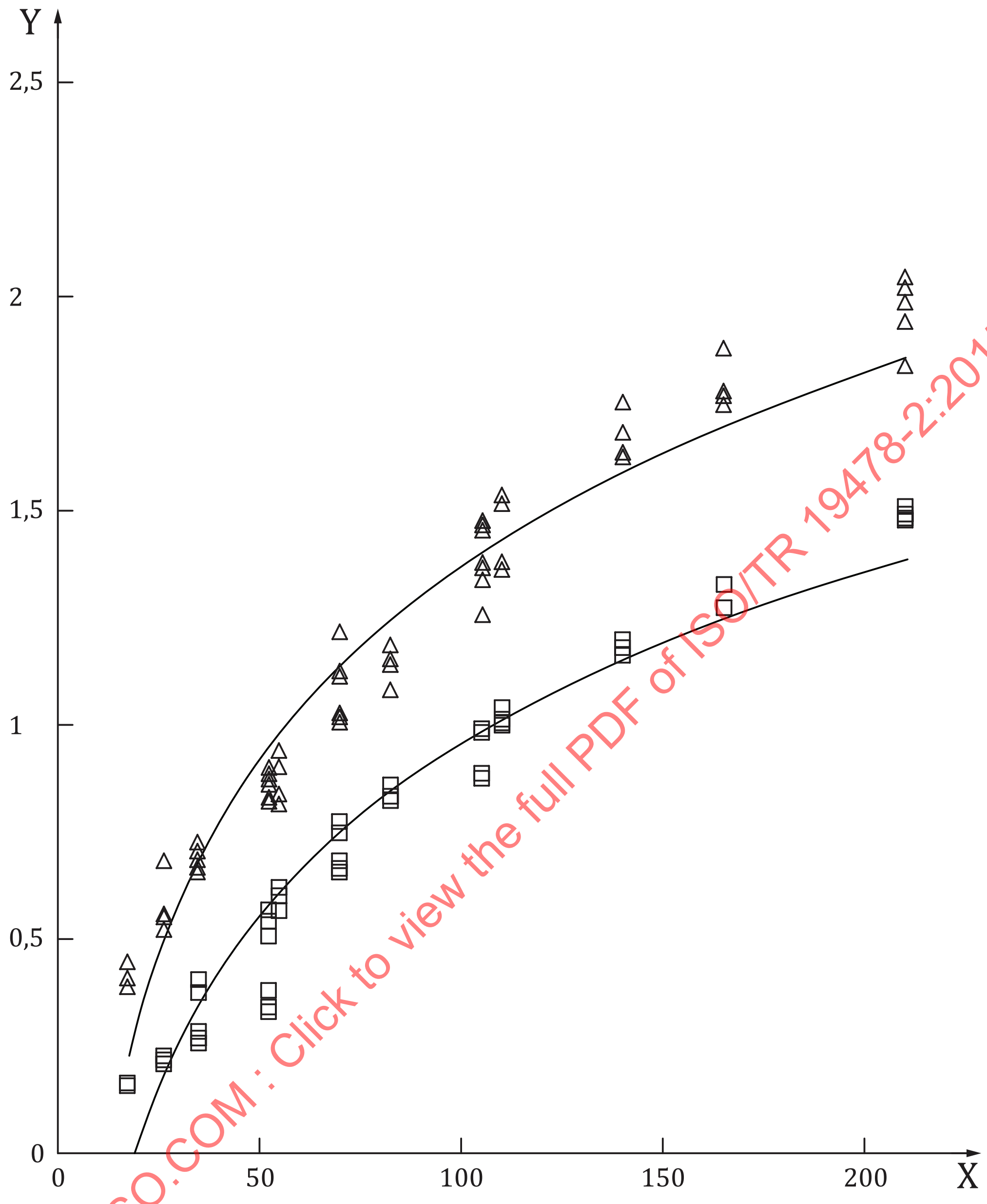
X puffing intensity (ml/min)

Y NFDPM yield (mg/cig)

□ L

△ LV

Figure 10 — NFDPM yield versus puffing intensity for products L and LV from 2011 study (A.14)



Key

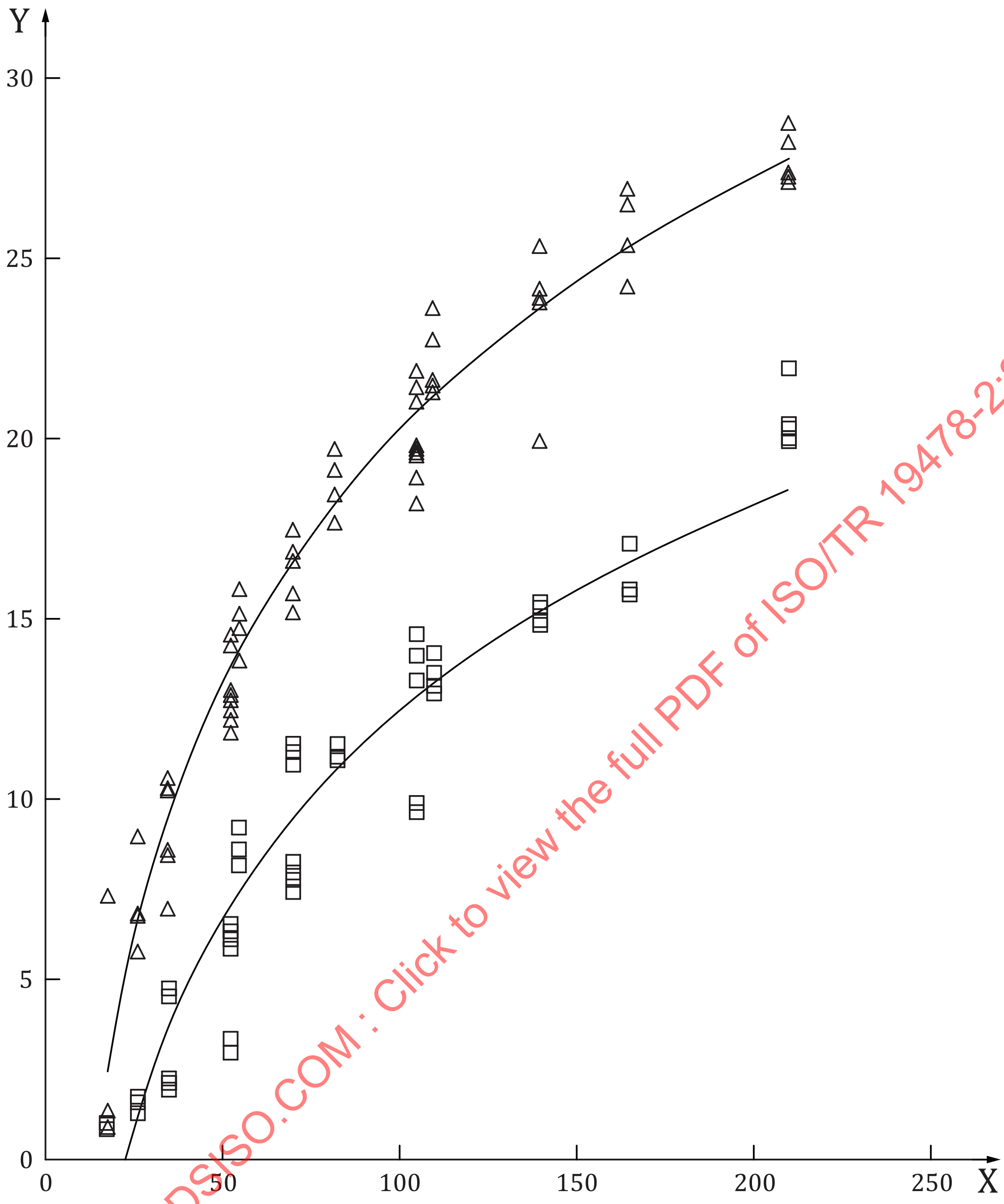
X puffing intensity (ml/min)

Y nicotine (mg/cig)

□ L

△ LV

Figure 11 — Nicotine yield versus puffing intensity for products L and LV from 2011 study (A.14)



Key

X puffing intensity (ml/min)

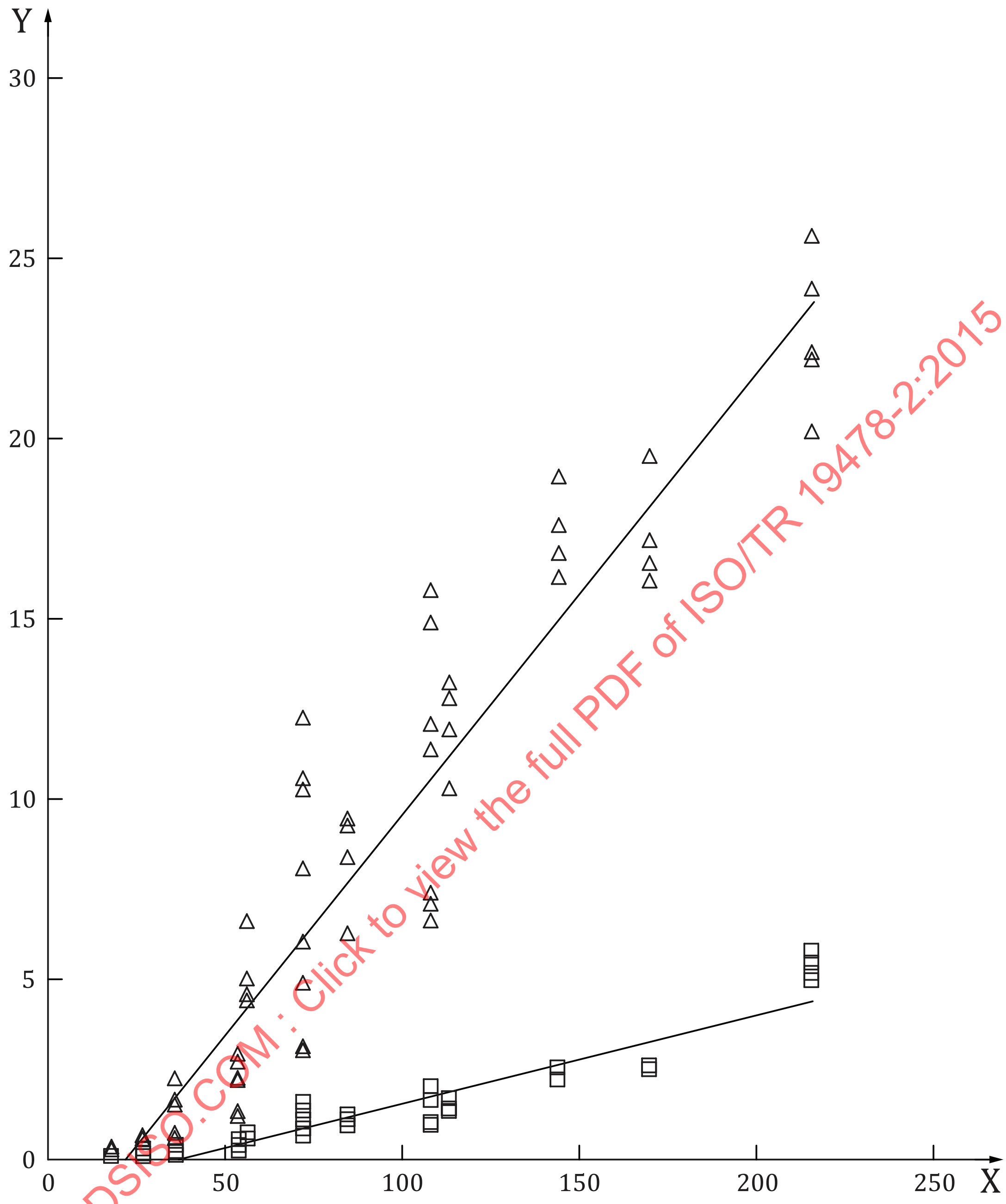
Y CO (mg/cig)

□ L

△ LV

Figure 12 — CO yield versus puffing intensity for products L and LV from 2011 study (A.14)

Figure 13 shows the water yields plotted against puffing intensity. The trend in the data is the same as for the 1980s study with the change in yield being better reflected by a linear fit to the data.



Key

X puffing intensity (ml/min)

Y water (mg/cig)

□ L

△ LV

Figure 13 — Water yield versus puffing intensity for products L and LV from 2011 study (A.14)

The overall conclusion from analysing and comparing the data from the 1980s and 2011 studies is that the trends in the change in smoke yields with increasing puffing intensity are very similar in spite of the different cigarette designs and blend styles. The TNCO yields are logarithmically related to puffing intensity whereas water yields are linearly related. As a consequence, the water yield increases relative to the other smoke components and becomes a major component of the combined smoke particulate and vapour phases when using the HCI regime.

5.6 Factors relevant to understanding how cigarettes burn and their use for predicting smoke yield

5.6.1 A review of additional studies

It is apparent that establishing relationships of the type identified in 5.5 might provide a means of predicting smoke yields. The most easily predicted smoke property is the total puff volume, i.e. total smoke volume, taken to completely smoke a cigarette, since the cigarette is consumed by taking puffs of a fixed, preset volume at a fixed, preset frequency. The only unknown is the length of time taken to smoke the cigarette to the specified butt length which can be estimated from the puff number or burn rate of the cigarette.

The puff number data from the 1980s study (Table 2) was used to estimate the average burn rate (B) for the cigarette. The burn rate, B, is:

$$B = L/T \quad (1)$$

where

B is the burn rate, in millimetre per minute;

L is the length burnt, in millimetre;

T is the smoking time, in minutes.

and

$$T = (N - 0{,}5)/F$$

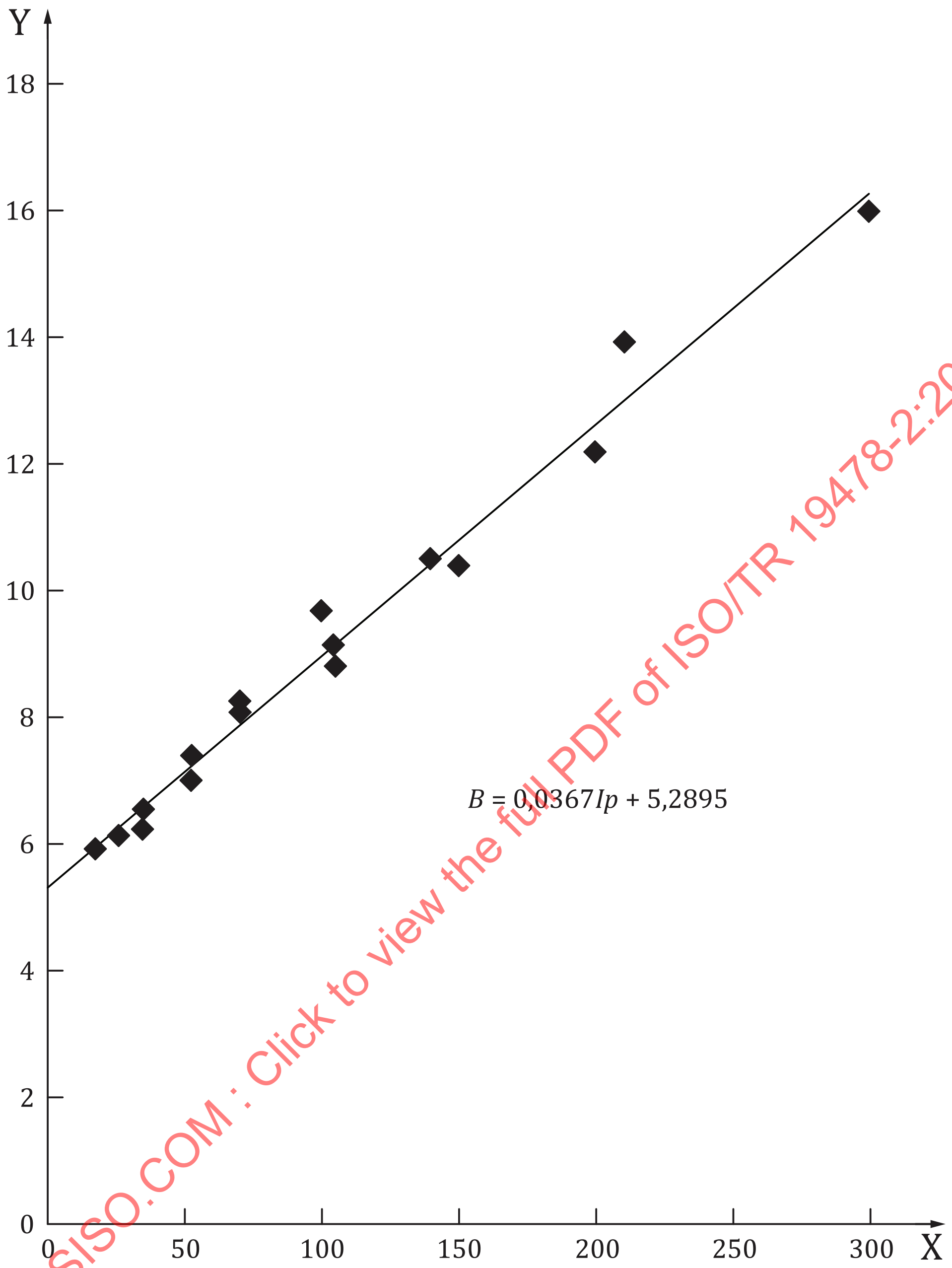
N is the puff number;

F is the puff frequency, in puffs per minute.

So:

$$B = L \times F/(N - 0{,}5) \quad (2)$$

The values of burn rate, calculated from the above relationship, are plotted against the corresponding values of puffing intensity (Ip) in Figure 14.



Key

X puffing intensity (ml/min)

Y burn rate (mm/min)

Figure 14 — Burn rate versus puffing intensity for 15 mg ISO tar brand from 1980s study (A.9)

The plot shows a good correlation between burn rate and puffing intensity so that the burn rate is defined by:

$$B = Ip \times C + S \tag{3}$$

where

Ip is the puffing intensity;

C is a constant;

S is the smoulder burn rate.

The fitted trend line shows a linear increase in burn rate from a fixed value at zero puffing intensity. The intercept on the y-axis gives the value for the smoulder rate of the cigarette i.e. the natural burn rate when no puffs are taken on the cigarette. The linear fit indicates that the burn rate increases at a fixed rate, given by the value of the slope so that the increase is directly proportional to the increase in puffing intensity.

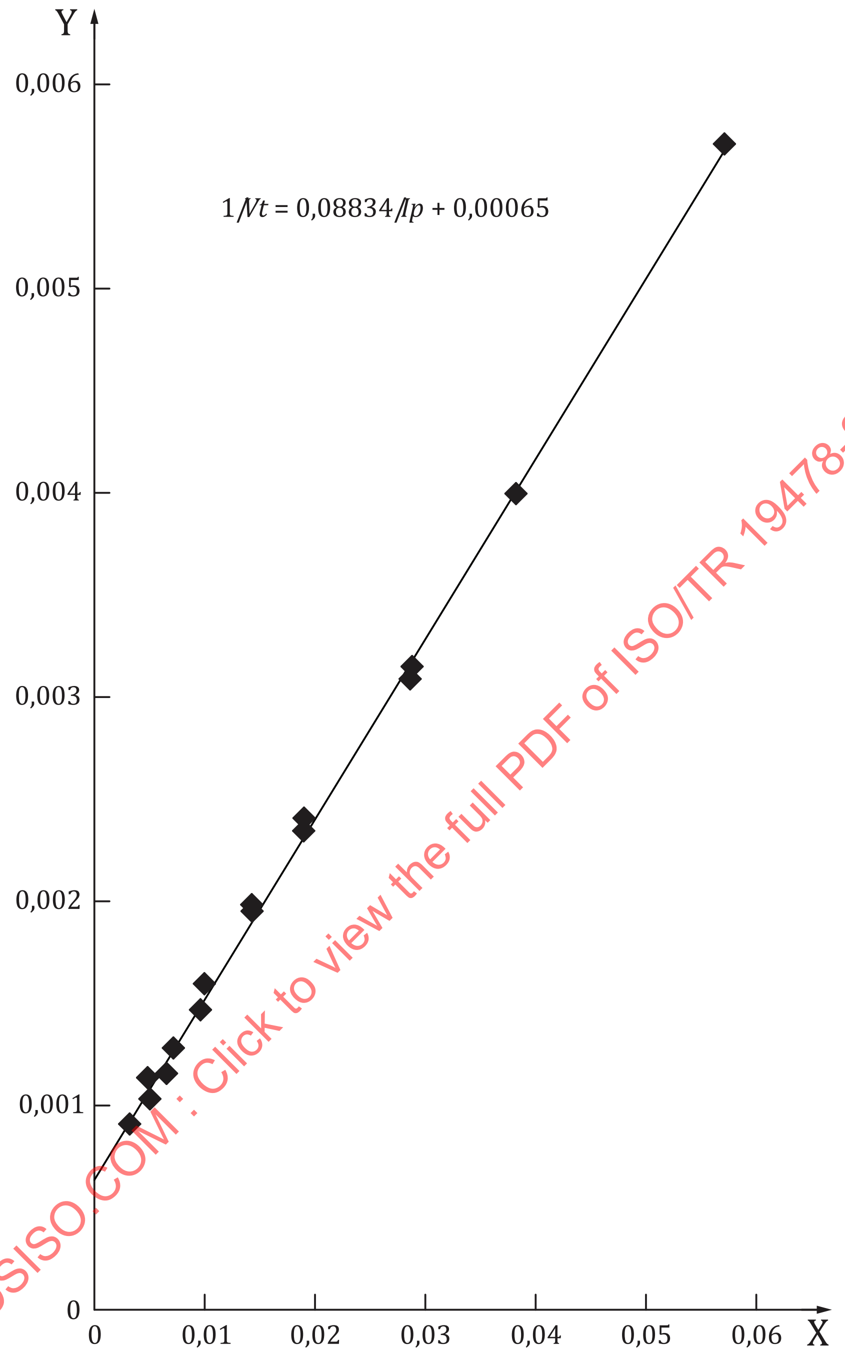
It is of interest to note that Formula (3) can be used to link the total smoke volume (Vt) with puffing intensity (Ip) since:

$$Vt = Ip \times T = Ip \times L/B = Ip \times L/(Ip \times C + S)$$

which transforms to:

$$L/Vt = (S/Ip) + C \tag{4}$$

The plot of $1/Vt$ against $1/Ip$ in Figure 15 confirms the relationship.



Key

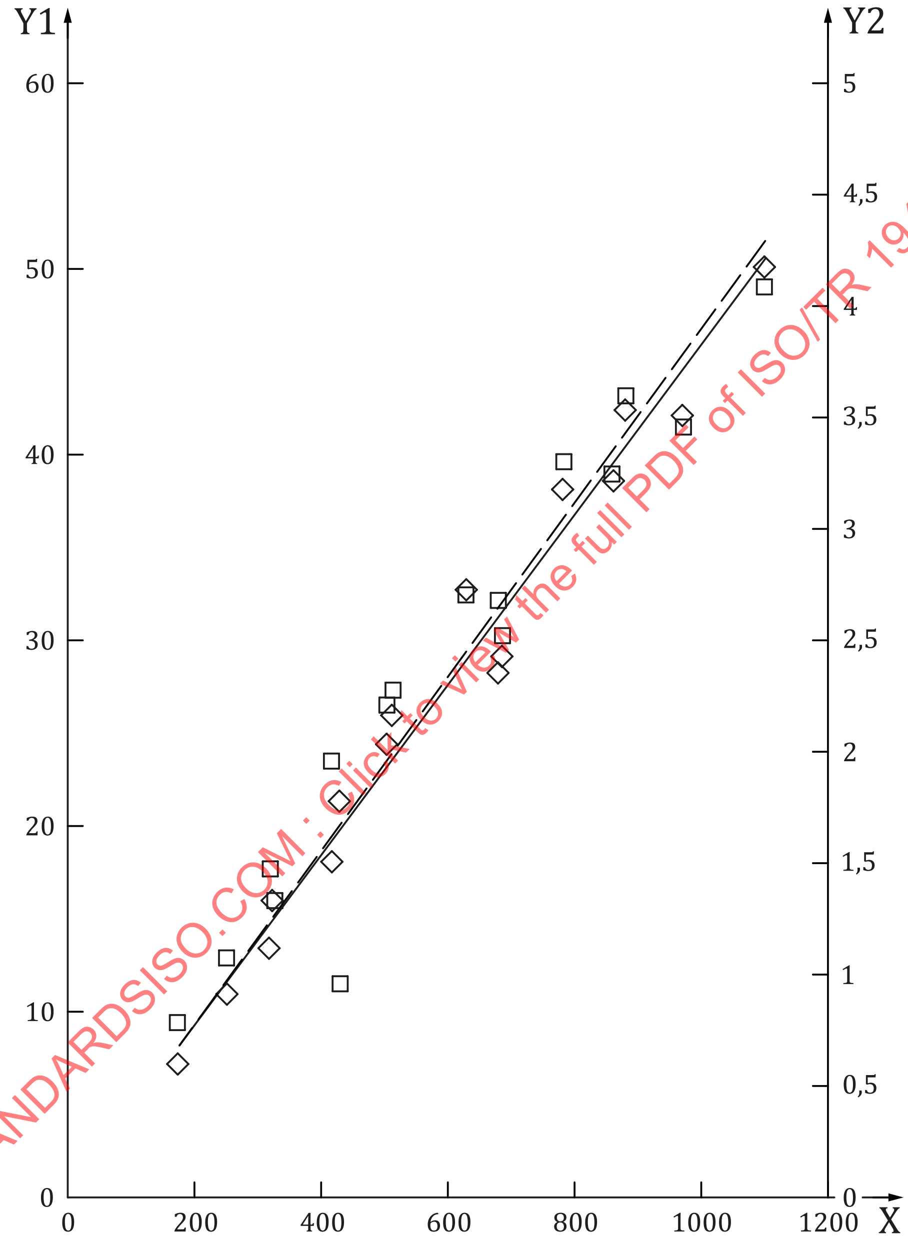
X puffing intensity^{-1} (ml/min)$^{-1}$

Y total smoke volume^{-1} (ml^{-1})

Figure 15 — 1/Total smoke volume versus 1/puffing intensity for 15 mg brand from 1980s study (A.9)

The above finding indicates how a cigarette is consumed during smoking. Once lit, the rate of consumption is initially determined by the natural burn rate (smoulder rate), which depends on the product design, and this is increased by puffing. The additional quantity of tobacco consumed during puffing is directly proportional to the volume of air drawn into the cigarette during puffing.

The next point for consideration is the “conversion” of tobacco into smoke. The simplest way to examine this is to compare the quantity of smoke produced with the volume of air drawn into the cigarette to burn the tobacco. In Figure 16, the total smoke volume taken to smoke the cigarette is plotted against the NFDPM and nicotine yields for the 15 mg ISO product from the 1980s study. The two variables are shown to be directly proportional for both smoke components. This indicates that both the amount of tobacco consumed and mainstream smoke produced are proportional to the volume of air drawn into the cigarette when puffing. The same trends were found with the 2011 study measurements of NFDPM, nicotine and carbon monoxide from the two products L and LV, as shown in Figures 17, 18 and 19. This finding from the two studies indicates that there is little change in the concentration of these components in tobacco smoke over a large range of smoking intensities.



Key

X total puff volume (ml/cig)

Y1 NFDPM yield (mg/cig)

Y2 nicotine yield (mg/cig)

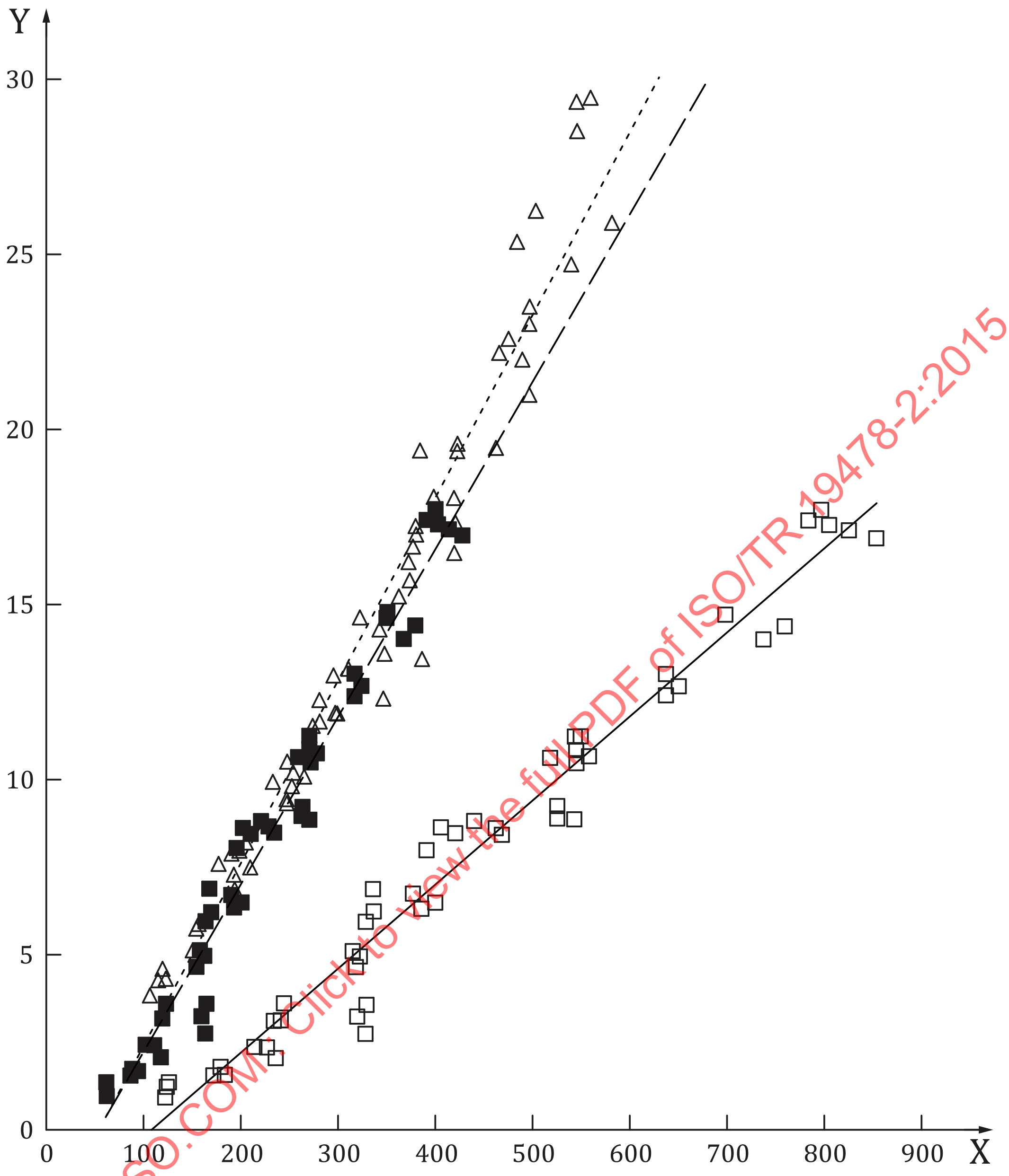
◇ NFDPM

□ nicotine

——— linear (NFDPM)

— — linear (nicotine)

Figure 16 — NFDPM and nicotine yield versus total puff volume for 15 mg ISO tar brand from 1980s study (A.9)



Key

X total puff volume (ml/cig)

Y NFDPM yield (mg/cig)

□ L

△ LV

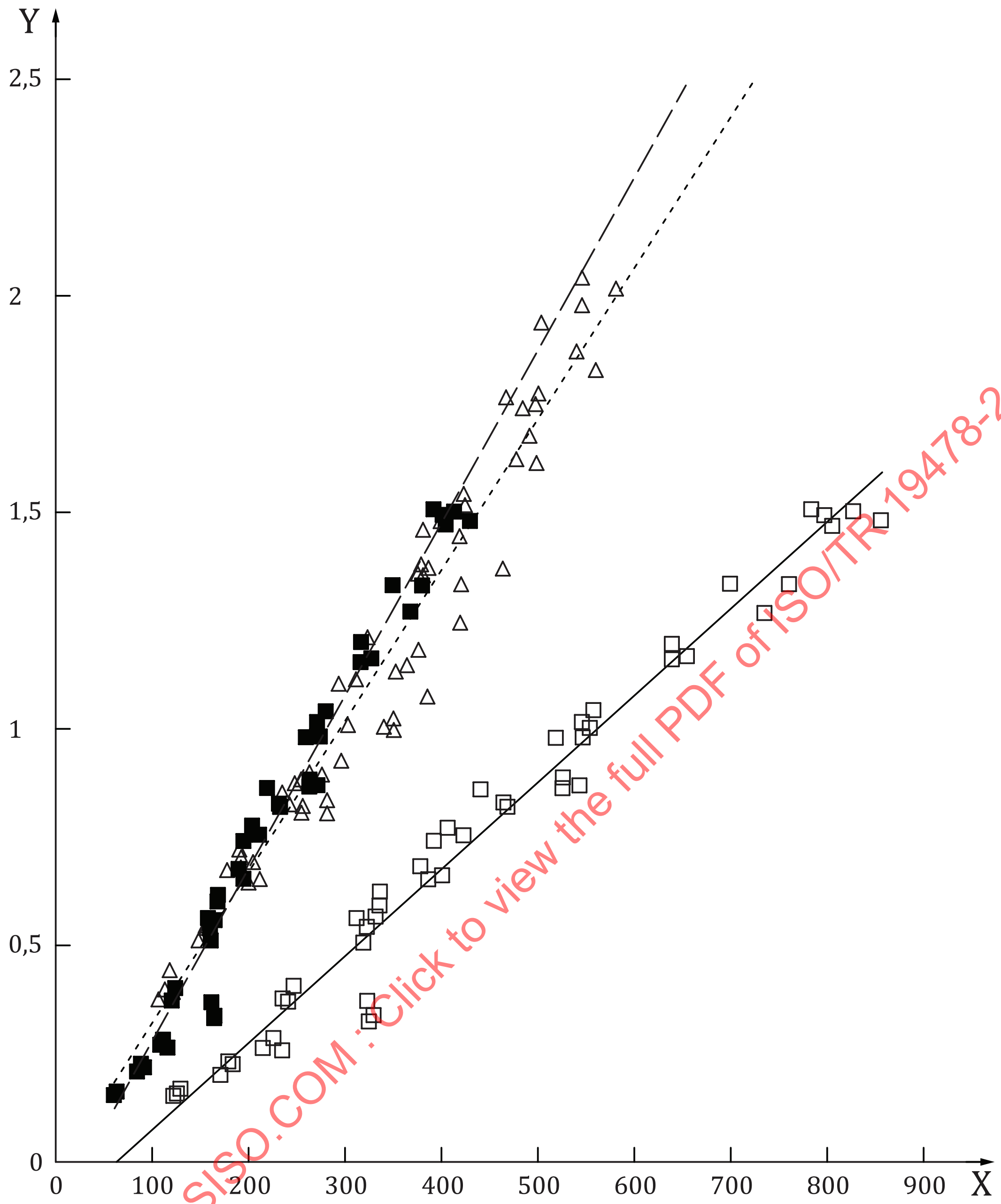
■ LC

——— linear (L)

- - - - - linear (LV)

— — linear (LC)

Figure 17 — NFDPM yield versus total puff volume for 2011 study (A.14)



Key

X total puff volume (ml/cig)

Y nicotine yield (mg/cig)

□ L

△ LV

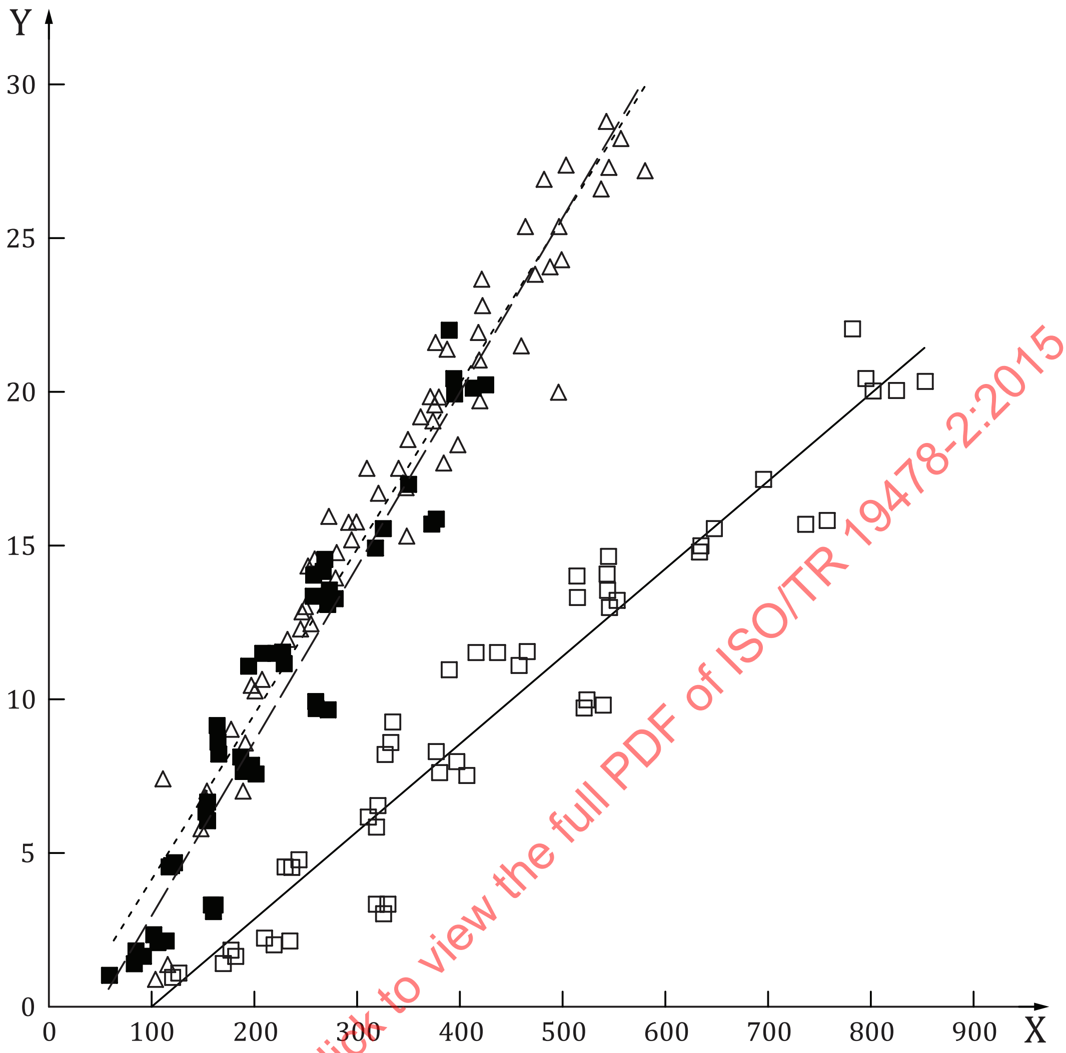
■ LC

——— linear (L)

- - - - - linear (LV)

— — linear (LC)

Figure 18 — Nicotine yield versus total puff volume for 2011 study (A.14)



Key

X total puff volume (ml/cig)

Y CO yield (mg/cig)

□ L

△ LV

■ LC

——— linear (L)

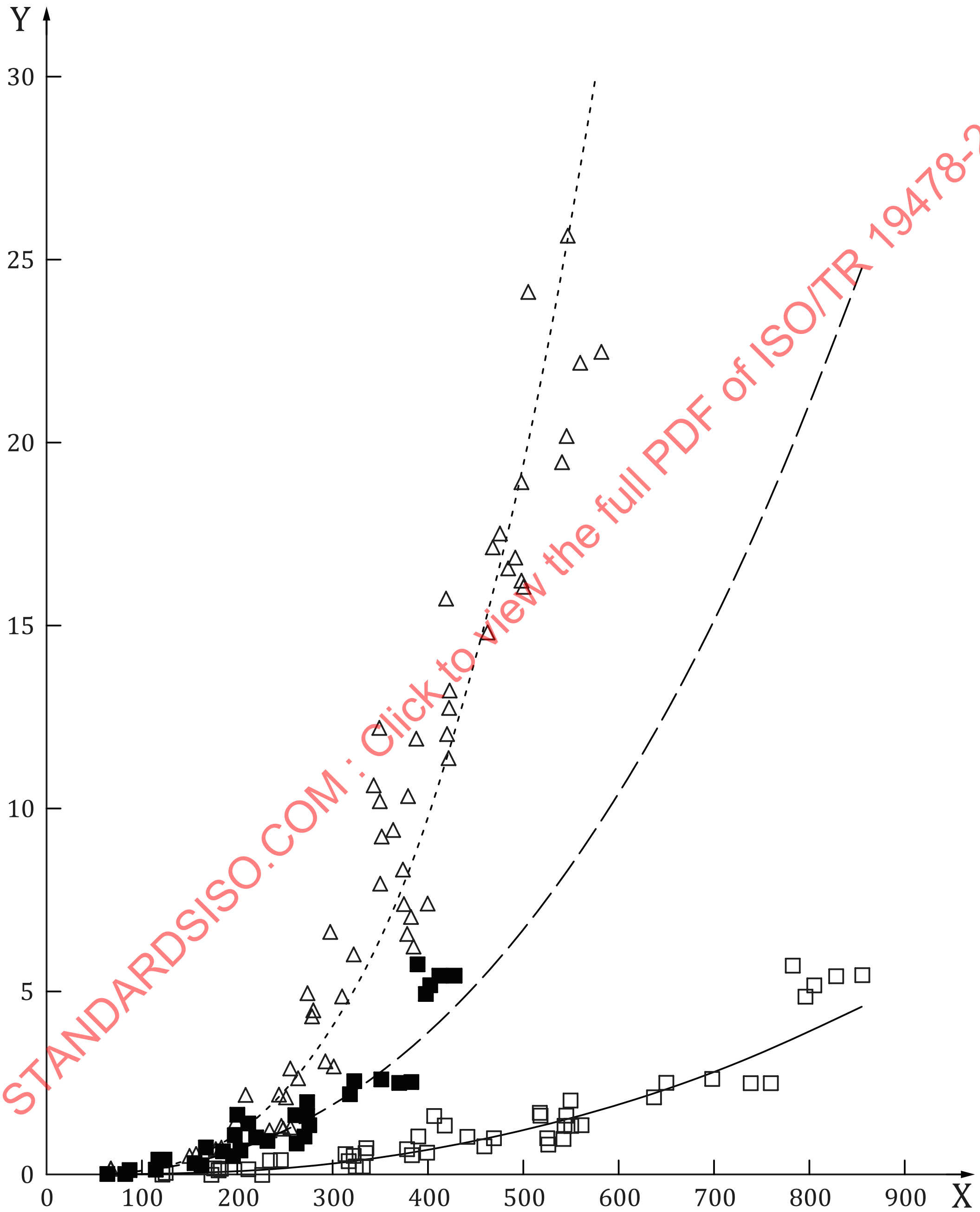
- - - - - - linear (LV)

— — linear (LC)

Figure 19 — Carbon monoxide yield versus total puff volume for 2011 study (A.14)

Since the same product was smoked with the ventilation holes open (L) and blocked (LV) in the 2011 study, the yields can be compared with respect to the puff volume at the cigarette coal. As the filter ventilation was known (49 %), it was possible to calculate the puff volume upstream of the filter ventilation holes, i.e. set puff volume × 0,51. This "coal" volume is slightly higher than the true coal volume as it also includes a small volume of air drawn through the cigarette paper. The total "coal" puff volumes designated as LC were calculated as 0,51 of the values for L and added to the plots for L and LV in Figures 17, 18 and 19. The agreement between the data for LC and LV is extremely good, providing further support for the assumption that the production of these smoke components is proportional to the puff volume at the cigarette coal.

In contrast, when the water yield values for total "coal" volume LC are compared with those from LV in Figure 20, the agreement is very poor. The values of water yield for LC are much lower than the values for LV at matched values of total puff volume. Since there is no reason why the water yield produced at the coal when smoking the L product should differ from those for LV at a matched coal puff volume, it must be concluded that water is "lost" from the smoke after it meets the ventilation air drawn into the cigarette through the filter ventilation holes. The term "lost" needs to be qualified as there appear to be two possible explanations for the reduction in the expected smoke water content. One is that the ventilation air cools the smoke and the water condenses in the cigarette filter and the other that it remains in the smoke vapour phase by mixing with the ventilation air to reduce the vapour pressure, but is not then collected in the CFH. This finding is important and an indication of possible difficulties in the gravimetric determination of TPM and NFDPM when the water becomes a major component of smoke condensate due to the use of an intense smoking regime.



Key

X total puff volume (ml/cig)

Y water yield (mg/cig)

□ L

△ LV

——— pot. (L)

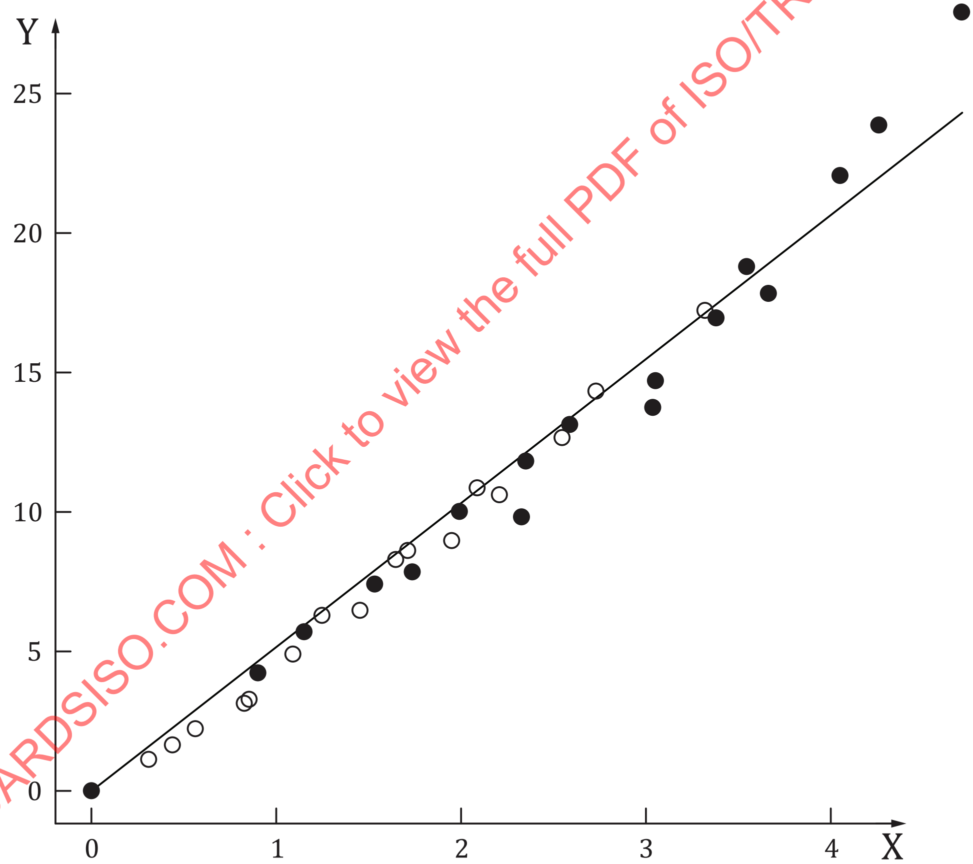
- - - - - - pot. (LV)

— — pot. (LC)

■ LC

Figure 20 — Water yield versus total puff volume for 2011 study (A.14)

The understanding of the smoking process from studies of the type reviewed above has provided the basis of models to predict the burn rate of cigarettes and link it to smoke yields. The models have, in general, been based upon linking the puff volume drawn into the cigarette at the coal with the increase in the amount of tobacco burnt in comparison with the smoulder burn. To do this, they need to take into account the various components of the air flow into the cigarette such as that through the coal, cigarette paper and cigarette filter. Such a model (A.27), based upon the sequential burning of a tobacco rod through successive puffing and smouldering periods, was shown to be capable of accurately predicting the burn rate and burn time of cigarettes over a wide puffing intensity range. The model was evaluated through comparison with experimental data from smoking a commercial 83 mm long, ventilated (52 %) filter cigarette. The cigarette was smoked using four puffing frequencies and puff volumes, and with the filter ventilation holes both open and blocked. The model could be used to calculate the reduction in the time, Δ*T*, required to smoke a cigarette due to puffing it as opposed to letting it smoulder burn completely. Δ*T* was found to be directly proportional to the NFDPM, nicotine and carbon monoxide yields, Figures 21, 22 and 23 respectively, and independent of having the filter ventilation holes open or blocked during smoking. Although Δ*T* was also independent of vent blocking when correlated with the water yields, these increased more rapidly than the other smoke components resulting in a better fit to an exponential trendline, Figure 24.

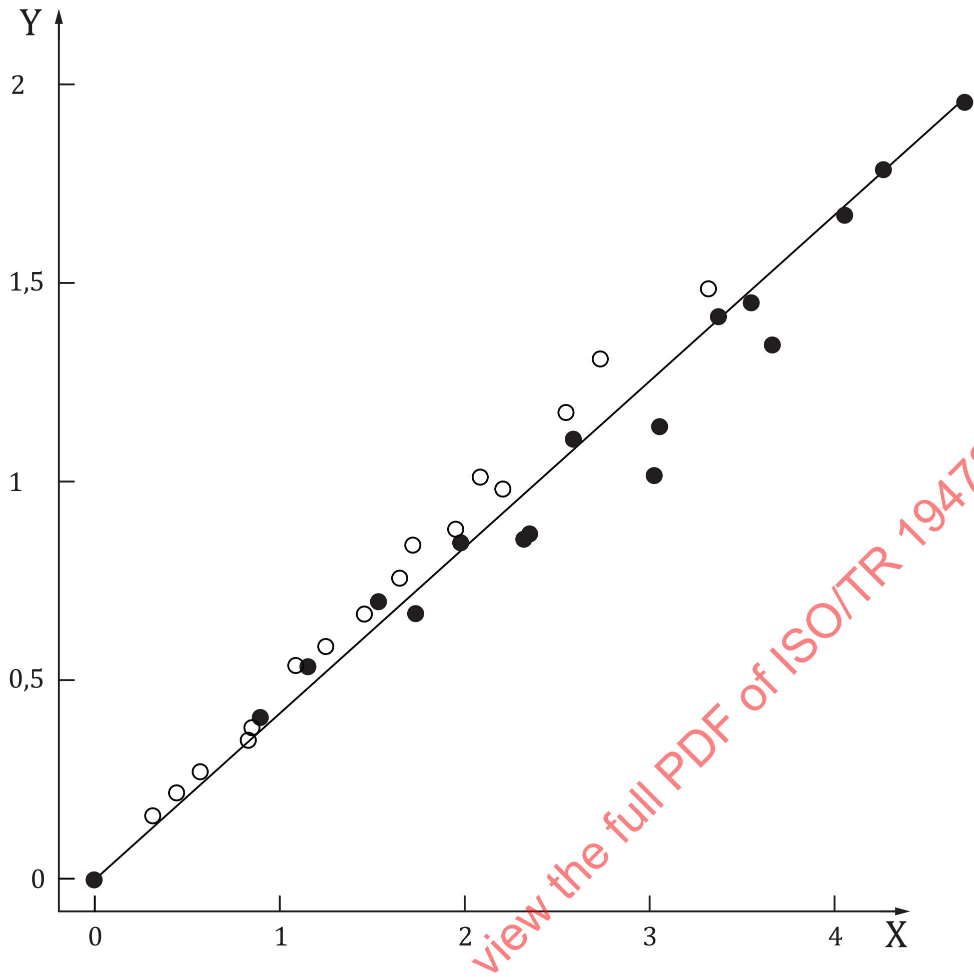


Key

X time of smouldering — time of smoking (min) ● vents blocked

Y NFDPM (tar) (mg/cig) ○ vents open

Figure 21 — NFDPM (tar) yield versus Δ*T* for A.27 study



Key

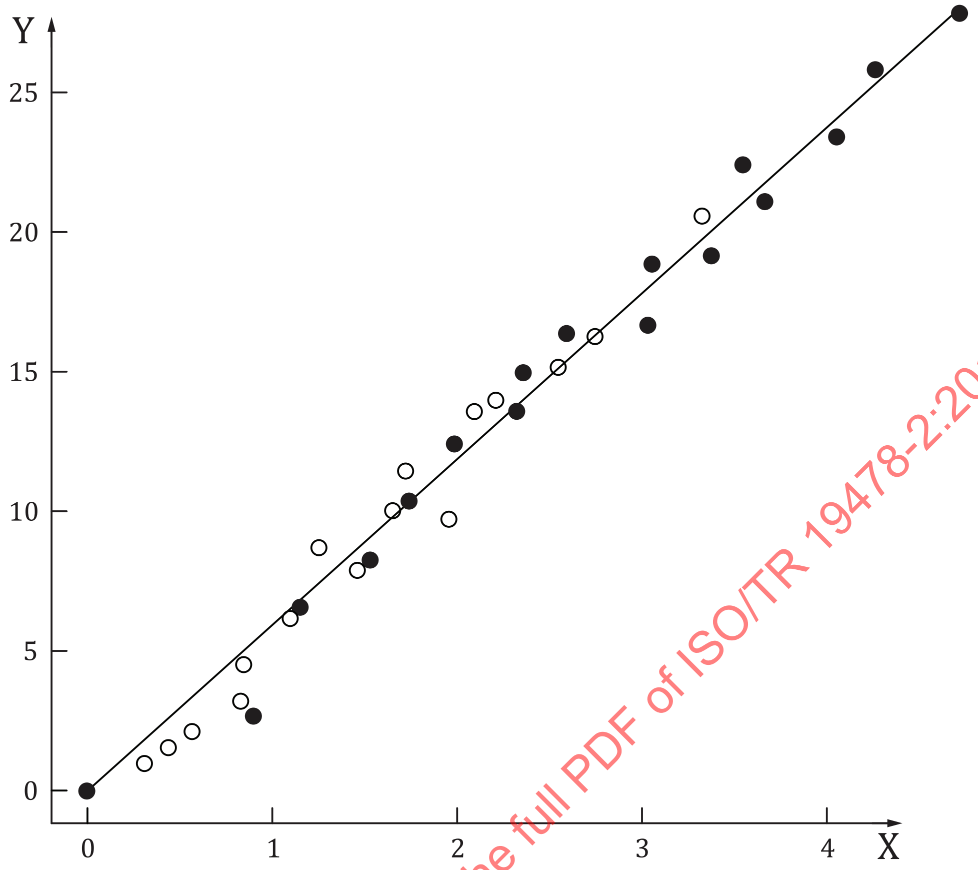
X time of smouldering — time of smoking (min)

Y nicotine (mg/cig)

● vents blocked

○ vents open

Figure 22 — Nicotine yield versus Δ*T* for A.27 study



Key

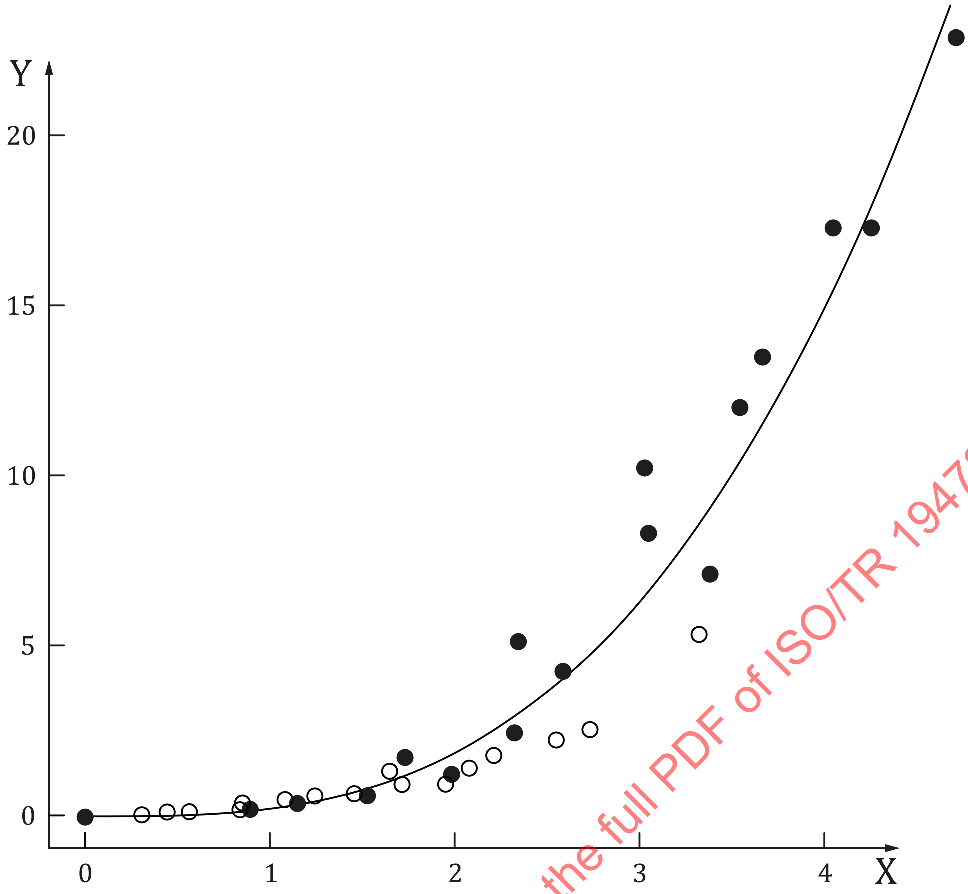
X time of smouldering — time of smoking (min)

Y CO (mg/cig)

● vents blocked

○ vents open

Figure 23 — Carbon monoxide yield versus Δ*T* for A.27 study



Key

X time of smouldering — time of smoking (min)

Y water (mg/cig)

● vents blocked

○ vents open

Figure 24 — Water yield versus Δ*T* for A.27 study

5.6.2 A review of WG 10 study data

It is also of interest to review the data from the WG 10 study to see if it agrees with the findings for the 1980s study and 2011 study. Table 5 gives the ratio of the yields for the HCI and ISO regimes together with the corresponding ratio of the total volumes of air drawn through the coal.

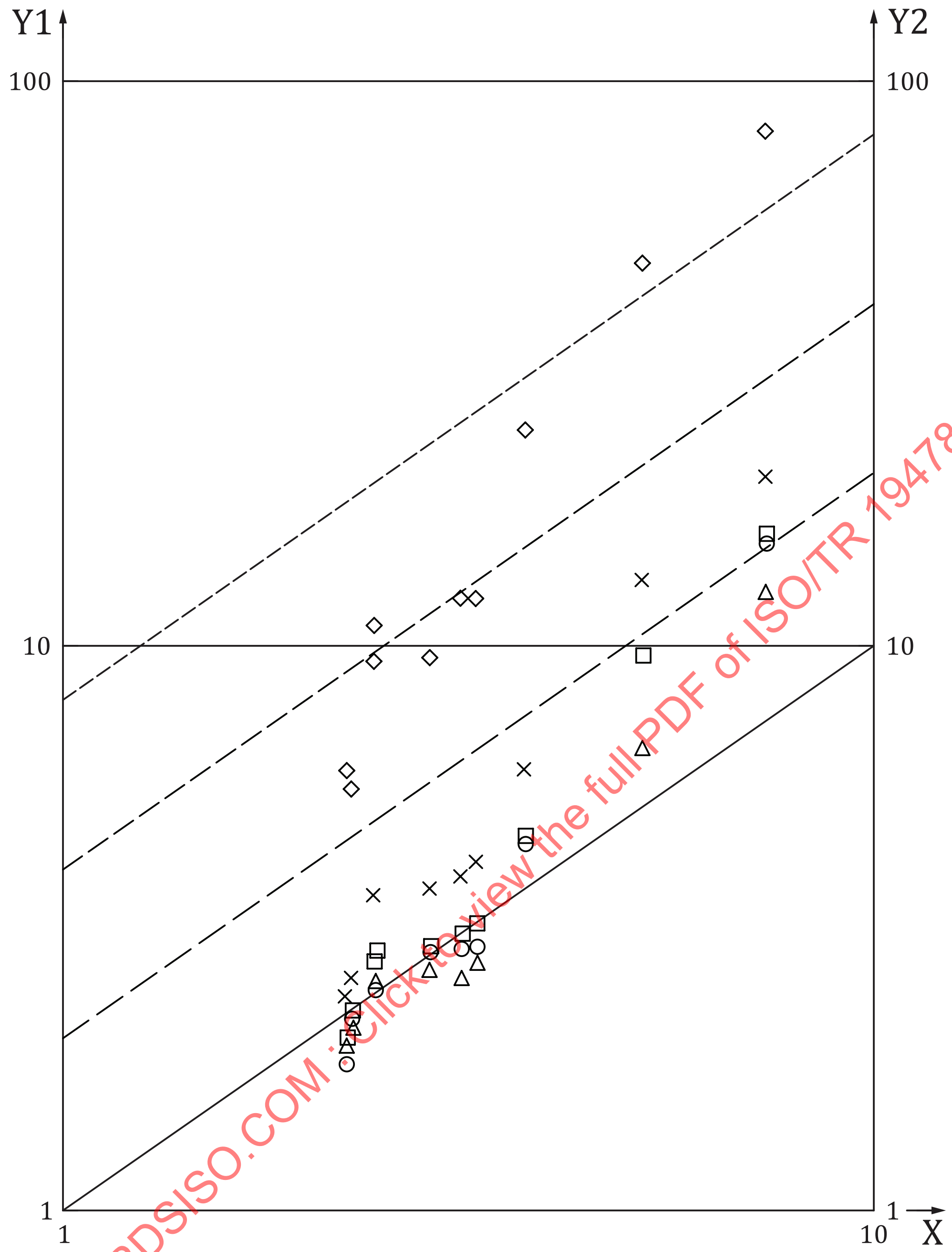
Table 5 — WG 10 study — Relative HCI/ISO smoke yields

Product	Filter ventilation (%)	Ratio HCI/ISO					
		TPM	Nicotine	Water	NFDPM	CO	Total Coal Volume
A	76	20,0	12,6	81,6	15,7	15,3	7,42
B	52	6,0	3,5	24,1	4,6	4,4	3,73
C	26	3,7	2,7	9,5	2,9	2,9	2,84
D	34	3,9	2,6	12,2	3,1	2,9	3,12
E	0	2,6	2,1	5,6	2,3	2,2	2,28
F	42	4,1	2,7	12,1	3,2	2,9	3,25
G	18	3,6	2,5	9,4	2,8	2,5	2,43
H	22	3,6	2,5	10,8	2,9	2,5	2,43
I	71	13,0	6,6	47,5	9,7	8,9	5,23
J	0	2,4	2,0	6,0	2,0	1,8	2,25

The Total Coal Volume, TCV, is calculated as:

TCV = Puff number × Puff volume × (100-% Filter ventilation)/100

The ratios for the water, TPM, NFDPM, nicotine and carbon monoxide yields are plotted against the corresponding Total Coal Volume ratios in Figure 25 using a logarithmic scale on both the *X*- and *Y*-axis. To assist with the comparison of the yield and TCV data, lines are included in Figure 25 to indicate where the increase in the HCI/ISO yield ratio is equal to, twice, four times or eight times the HCI/ISO TCV ratio. The plot shows that the relative yields of NFDPM, nicotine and carbon monoxide for eight of the 10 products are predicted from the relative change in the TCV drawn through the coal to smoke them as indicated by the proximity of the data to the 1 to 1 line for these smoke components. The conclusion drawn from this is that the concentration of the smoke components at the cigarette coal is the same for the two smoking regimes, and in agreement with the expectations from the 1980s and 2011 studies above.



Key

X	HCI/ISO total coal volume ratio	×	TPM
Y1, Y2	HCI/ISO yield ratio	□	NFDPM
————	Y = 1X	△	nicotine
— —	Y = 2X	○	CO
— — —	Y = 4X	◇	water
– – – –	Y = 8X		

Figure 25 — HCI/ISO yield ratio versus total coal volume ratio for water, TPM, NFDPM, nicotine and carbon monoxide (WG 10 TNCO study data)

The yield ratios of the two highly ventilated products, A (76 %) and I (71 %), are much greater than expected from the TCV ratios. The most probable explanation is that, although the concentration of the smoke components is the same when the smoke is formed at the cigarette coal, it is reduced to a greater extent in transit through the cigarette in comparison with the other eight products. The much reduced smoke velocity increases filtration efficiency in the tobacco rod and filter upstream of the filter ventilation holes. The filter retention measurements in Table 2 illustrate this trend with the filter retention falling as the puff volume, and hence flow rate, through the cigarette is reduced. Whereas the ISO regime flow rate through a cigarette with no filter ventilation would be 64 % of the HCI regime, for Product A, with 76 % ventilation, it would be reduced to only 15 % of the HCI regime upstream of the filter ventilation holes.

The yield ratios for the water in Figure 25 are well above the corresponding 1 to 1 line for the data, being about 10 for ventilation levels below 30 % to 40 % but then increasing rapidly to more than 80 at 76 % filter ventilation. The yield ratios for TPM are greater than those for NFDPM as would be expected from the increased water content.

The conclusions drawn from this analysis of the WG 10 study data support the assumption used in models that, when smoke forms at the cigarette coal, the concentration of the main smoke components is relatively fixed for a given product. It also shows, however, that it can be modified in transit through the cigarette, with greater changes occurring at very low flow rates.

6 Comparison of the design and performance of rotary and linear smoking machines

6.1 A review of information relevant to conclusion j) of ISO/TR 19478-1:2014

Conclusion j) stated,

"*It has been observed in this study that the smoking machine type seems to be the major contributor to the between-laboratory variability of the intense smoking regime. In fact, and in contrast to the ISO smoking regime, extreme differences can be observed between the two smoking machine types for most of the measured parameters: higher values for TPM, nicotine, water and NFDPM and lower values for CO can be observed for linear smoking machines (and vice versa for rotary smoking machine type).*"

Conclusion j) first acknowledges the robust nature of the ISO smoking standards when used with the ISO smoking regime. Comparison of the measurements from the two machine types as a ratio (see Table 6) indicates little to no difference for all the measured smoke analytes apart from water. The lower water yield measured on the linear machine can be explained by losses from the CFH during smoking five cigarettes sequentially. The RH of the early puffs on each cigarette will be about 60 %, the same as the ambient air, and will strip off water deposited from the later puffs, with a much higher RH, of the previous cigarette. This will not happen on a rotary machine as all cigarettes are smoked consecutively with the TPM collected by a single CFH. As a result, the RH of the smoke being collected increases continuously over the course of the smoking run. It should also be noted that the difference in water yield does not impact on the agreement in the calculated NFDPM yield.

Table 6 — ISO smoke yields from WG 10 study as a ratio for linear and rotary machines

Product code	Ratio of ISO yields (Rotary/Linear)				
	TPM	Nicotine	Water	NFDPM	CO
A	1,09	0,91	1,25	1,07	1,00
B	1,03	1,00	1,29	1,01	1,11
C	0,97	1,01	1,17	0,94	1,08
D	0,98	1,00	1,31	0,95	1,03
E	0,92	1,00	1,20	0,89	1,03
F	0,99	0,96	1,30	0,96	1,02
G	1,00	1,00	1,31	0,96	1,04
H	1,00	0,97	1,27	0,97	1,06
I	1,06	1,00	1,64	1,03	1,07
J	0,95	0,96	1,16	0,93	1,03
Mean	**1,00**	**0,98**	**1,29**	**0,97**	**1,05**

Conclusion j) then contrasts the agreement in the measurements from the two machine types using the ISO regime with the differences using the HCI regime. The yield ratios in Table 7 highlight the major differences in TPM, water and NFDPM yields. This sets the need to understand how the changed smoke yield and composition when using the HCI regime impacted on its collection and analysis using the designs of smoking machines, equipment and procedures specified in ISO 3308:2000 and ISO 4387.

Table 7 — HCI smoke yields from WG 10 study as a ratio for linear and rotary machines

Product code	Ratio of HCI yields (Rotary/Linear)				
	TPM	Nicotine	Water	NFDPM	CO
A	0,85	0,96	0,75	0,88	1,05
B	0,80	0,97	0,68	0,84	1,05
C	0,82	0,96	0,68	0,87	1,03
D	0,80	0,96	0,67	0,85	1,05
E	0,85	0,95	0,80	0,86	1,02
F	0,86	0,95	0,76	0,88	1,03
G	0,82	0,96	0,71	0,85	1,04
H	0,84	0,96	0,74	0,88	1,03
I	0,78	0,96	0,69	0,79	1,06
J	0,91	0,96	0,85	0,89	1,03
Mean	**0,83**	**0,96**	**0,73**	**0,86**	**1,04**

The consistency of the ratio for all 10 products in Tables 6 and 7 indicates that product design variables have little influence on the value of the ratio and therefore do not impact on the differences in yield between the two machine types when changing from the ISO regime to the HCI regime. The consideration of cigarette design features does not provide a route for further investigation.

The two most obvious differences in design between the machines are the cigarettes being stationary or moved during smoking and the design of the collection system for TPM. The possibility that one, or both, of these differences could change the measured smoke yield should be considered. The lower TPM yields from the rotary machine might be due to the cigarette movement reducing the TPM leaving the cigarette for collection in the smoking machine, TPM depositing in the machine before reaching the CFH or the TPM composition being altered to allow more to pass through the CFH. The lower NFDPM yields could result from the lower TPM yields or be an indication of a problem with the measurement of smoke water when measuring the high yields from the HCI regime.

A review of the performance of the two machine types is more easily reported by breaking the smoking process into procedural and equipment blocks. This is done in Annex C with the smoking procedure divided into four phases and the equipment into three zones. This also makes possible a systematic comparison of the design and performance of rotary and linear smoking machines.

6.2 Zone 1: The cigarette zone

6.2.1 Airflow/cigarette movement

The control of the flow of air over the cigarette is important as it will influence the loss by diffusion of vapours and gases through the cigarette paper. Prior to smoking, the airflow is set as specified in ISO 3308:2000 to a speed of 200 mm/s at a point along the axis of the cigarette. The need to measure from a fixed point on the smoking machine when positioning the airflow probe results in the measurements being made at slightly different positions on the two smoking machine types, relative to the cigarette. Any difference in the air flow resulting from this procedure will be small and of no concern.

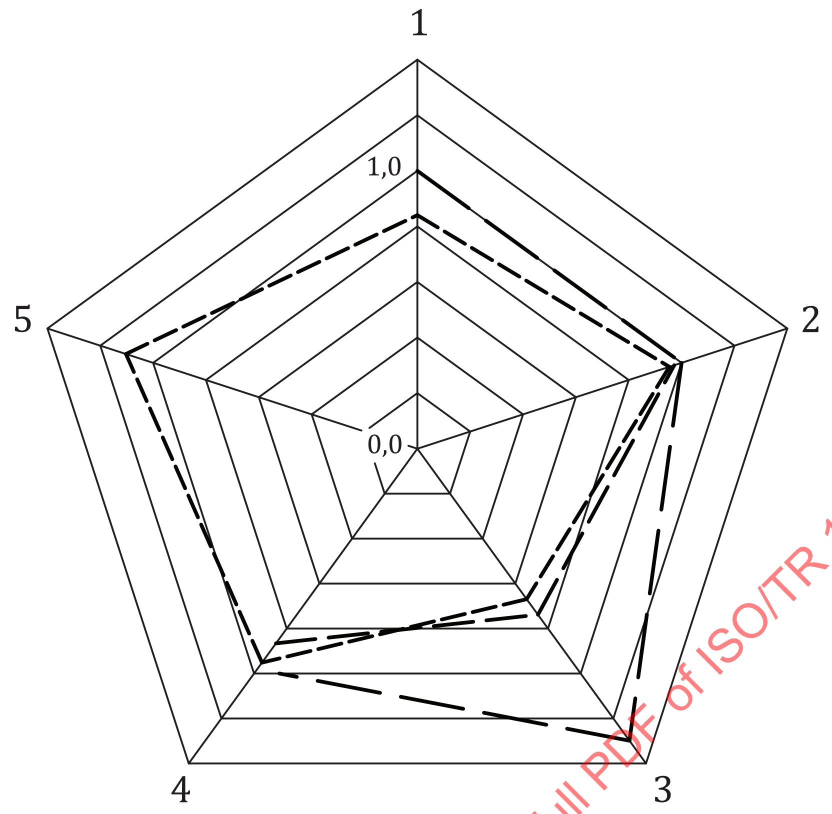
A greater difference will arise due to the differences in the basic geometry of rotary and linear machines. The layout of the two machine types is sufficiently different to make it impossible to provide the same air flow contours relative to the axis of a cigarette. While the same air speed might be set at approximately the same position on the cigarette axis, the direction of the airflow will be different on the two machine types. Specifying a common value for both speed and direction is not possible.

Another factor of relevance to the air flow over the cigarettes is whether they remain stationary or are moved during smoking. The cigarette holders on the linear smoking machine remain stationary whereas those on a rotary move through a 360 degree arc between puffs. The movement on the rotary machine obviously results in an additional air movement over the cigarettes.

Any change in yield due to a difference in air movement over the cigarettes is most likely to occur in the vapour phase compounds. Carbon monoxide is the only major vapour phase smoke component that is routinely measured using ISO methodology (ISO 8454). It, therefore, provides the most obvious means of looking at possible machine differences.

It can be seen from the carbon monoxide yield ratios for the two machines in Table 7 that the yield from the rotary machine is slightly higher (about 4 % on average) although the difference is not statistically significant. Even if the difference was meaningful, it is in the wrong direction to indicate the decrease in TPM yields from cigarettes during smoking on the rotary machine is due to an increased loss of vapour phase water.

This finding was supported by the A.21 study of the retention efficiency of cigarette filters for smoke water. The study involved smoking four channels of the same commercial cigarette product on both a rotary and linear smoking machine using the HCI regime. The TPM, water, NFDPM and nicotine yields were measured as well as the water retained by the cigarette filter tip. The rotary/linear yield ratios for these smoke analytes are plotted in Figure 26 together with the ratio of the water retained in the filter tip. The equivalent HCI data from the WG 10 study is also included to show the good general agreement with the A.21 data. Whereas the rotary/linear water yield ratio is similar and well below a value of one for both HCI data sets, the tip water ratio is slightly greater than one. This finding indicates that the water component of the smoke passing through the filter is the same for both the rotary and linear smoking machines. The reduction in the amount of water subsequently collected on the rotary machine cannot, therefore, be due to a difference in air movement over the cigarettes.



Key

1 TPM ratio (R/L)

2 nicotine ratio (R/L)

3 water ratio (R/L)

4 NFDPM ratio (R/L)

5 tip water (A.21 data only)

ISO-WG 10

HCI-WG 10

HCI A.21

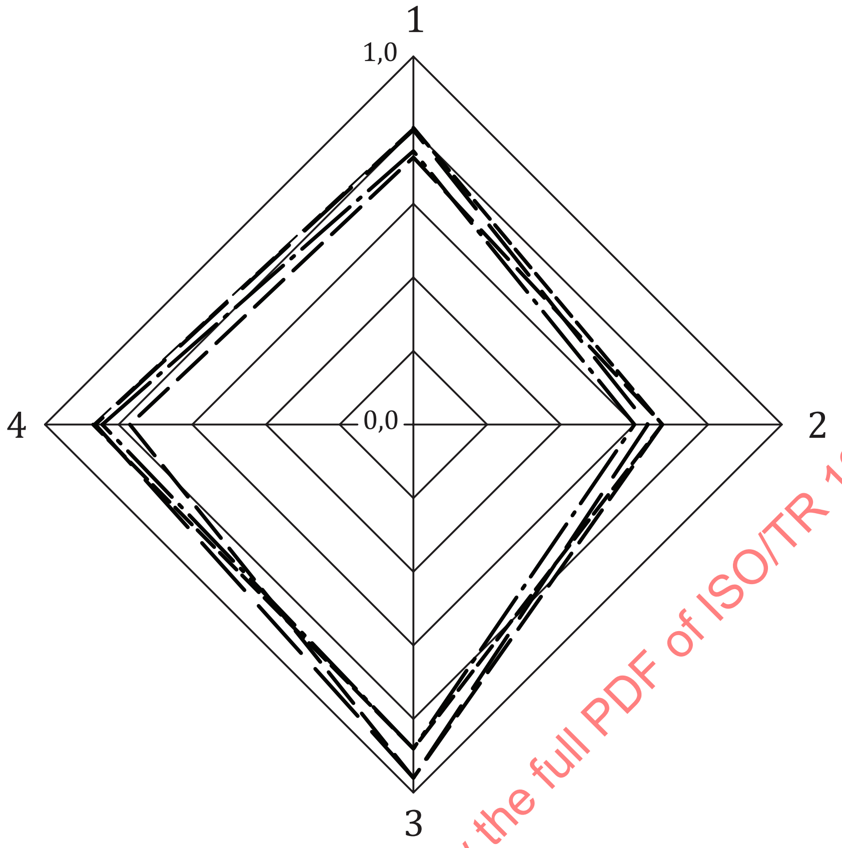
Figure 26 — Comparison of HCI smoke yields from the A.21 study as a machine ratio (rotary/linear) with the values from the WG10 TNCO study

Further evidence (A.17) that the yield differences between the two machine types was not caused by air flow differences or cigarette movement was provided by a study using a rotary machine capable of two operational modes of smoke collection. The first mode of operation was to use the machine normally apart from replacing the 92 mm CFH with a 44 mm CFH. The second mode of operation was to place a 44 mm CFH directly behind the cigarette holder so that the TPM collection simulated that of a linear machine while the cigarettes were subject to the normal rotational movement of a rotary smoking machine. The TPM from three cigarettes was collected onto each pad for the HCI regime and 9 or 10 channels were smoked for each operating mode. Four products were tested, one reference cigarette (Kentucky Reference Cigarette 3R4F) and three commercial products with ISO yields of 1 mg, 3 mg and 6 mg.

The TPM, water, nicotine and NFDPM yields for the study are given in Table 8 and together with the yield ratios from the two smoking modes. The yield ratios show that the yields for the HCI regime when using the normal rotary mode are lower than those using the linear mode and the pattern for the reduction in yield is very similar for the four products, Figure 27. The average ratios for the four products (Table 8) are similar to those found for the 10 products in the WG 10 study (Table 7) when comparing the yields from the two machines. The A.17 study data for the HCI regime is compared with both the ISO and HCI regime WG 10 study data in Figure 28. This plot clearly illustrates the good agreement of the A.17 data with the WG 10 study data for the HCI regime as well as the poor agreement with the data for the ISO regime from the WG 10 study. This finding indicates that the difference in the yields from the two machine types in the WG 10 study is due to the difference in the position of the CFH, and, conversely, is not due to the differences in air flow or cigarette movement.

Table 8 — HCI smoke yields from A.17 study as a ratio of two machines types (rotary/linear)

Product	Mode	TPM (mg)	Water (mg)	Nicotine (mg)	NFDPM (mg)
A (3R4F)	Rotary	36,77	12,45	1,89	22,43
	Linear	49,28	20,67	2,13	26,49
	Ratio	0,75	0,60	0,89	0,85
B (ISO-6 mg)	Rotary	30,11	9,01	1,48	19,62
	Linear	38,10	13,42	1,53	23,16
	Ratio	0,79	0,67	0,96	0,85
C (ISO-3 mg)	Rotary	25,59	8,64	1,31	15,64
	Linear	35,21	13,60	1,36	20,25
	Ratio	0,73	0,64	0,96	0,77
D (ISO-1 mg)	Rotary	27,38	7,39	1,50	18,50
	Linear	34,08	10,92	1,70	21,46
	Ratio	0,80	0,68	0,88	0,86
Mean	**Ratio**	**0,77**	**0,65**	**0,92**	**0,83**

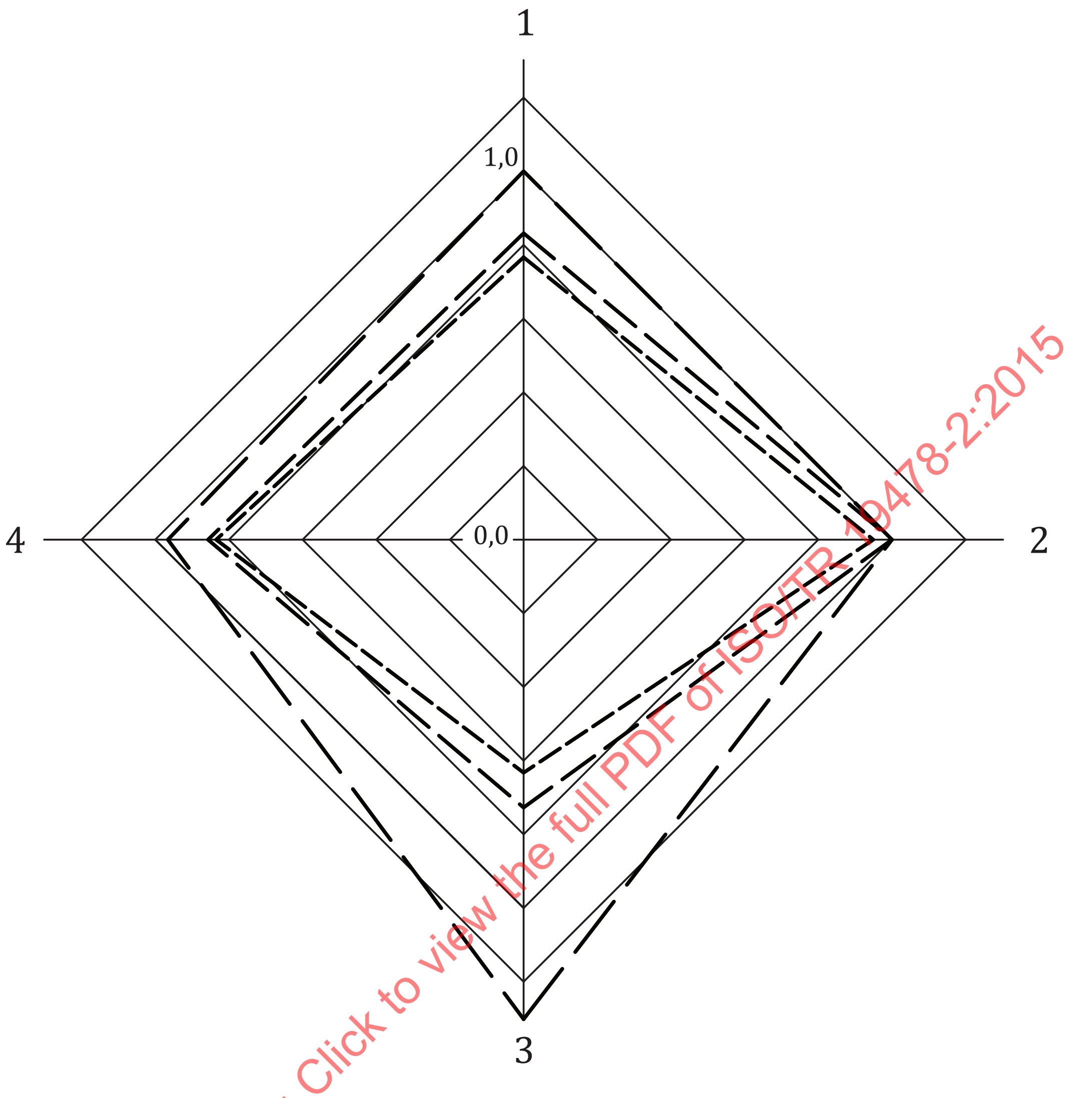


Key

1 TPM ratio (R/L)
2 water ratio (R/L)
3 nicotine ratio (R/L)
4 NFDPM ratio (R/L)

A (3R4F)
B (ISO-6 mg)
C (ISO-3 mg)
D (ISO-1 mg)

Figure 27 — Comparison of HCI smoke yields as a machine ratio (rotary/linear) from the four individual products in A.17 study



Key

1 TPM ratio (R/L)
2 nicotine ratio (R/L)
3 water ratio (R/L)
4 NFDPM ratio (R/L)

ISO-WG 10
HCI-WG 10
HCI- A.17

Figure 28 — Comparison of the average smoke yields as a machine ratio (rotary/linear) from the A.17 study and WG 10 TNCO study

6.2.2 Puffing

Although the basic smoking process whereby the suction mechanism draws a preset puff volume at a preset frequency is identical for both the machine types, there are procedural and environmental differences during the smoking process.

The standard linear machine has 20 independent smoking ports and suction mechanisms, allowing it to smoke up to 20 cigarettes simultaneously. Each cigarette on a linear machine is lit and puffed simultaneously during a single smoking run.

In contrast, on a rotary machine, the 20 cigarettes are lit and puffed sequentially. They are moved by the rotation of the carousel, on which the cigarette holders are mounted, between each puff to allow the single suction mechanism to be coupled to each port in turn.

These differences have a major impact on the pattern of the smoke flow into the CFH where it is collected for analysis. This is further discussed in 6.3.2 dealing with the CFH.

6.2.3 Termination of smoking

During a smoking run, the tobacco rod is allowed to burn until it reaches the butt length specified in ISO 4387, at which time the smoking process shall be stopped. The two devices used to terminate the smoking process operate on different scientific principles which impacts on the setting procedure as well as their relative speed of operation to terminate a smoking. Tests (A.28) with both devices mounted on the same smoking machine to monitor the smoking of the same cigarette have indicated a possible 0,5 s difference in response time when terminating a smoking run during a puff. The two types of termination devices are described in ISO 3308:2000, 5.4.8, as follows:

a) *a micro-switch activated by the burning through of a 100 % cotton, (48 ± 4) tex thread, placed on the butt mark;*

b) *a specially shielded infrared (IR) detector. The shielding defines a detection border plane perpendicular to the cigarette. The crossing of that plane by the burning cone terminates the puff.*

Device (a) is used on the linear machine. Each port has its own device and the port is designed to allow the cigarette holder to be moved along the axis of the cigarette to align the cotton with the butt mark on the cigarette. After setting, the cotton will break once the cigarette is smoked down and burns the cotton on the butt line. The device can only operate once and then needs the cotton to be replaced before the next cigarette is smoked. The procedure requires each cigarette to be butt marked and the mark aligned with the cotton thread before starting to smoke.

Device (a) cannot be used on a rotary machine as each smoking port and cigarette move between puffs. Instead, a single device (b) is used and positioned at a point corresponding with the average butt length for the cigarette type being smoked. It is, therefore, not necessary to butt mark the cigarettes prior to smoking on a rotary smoking machine.

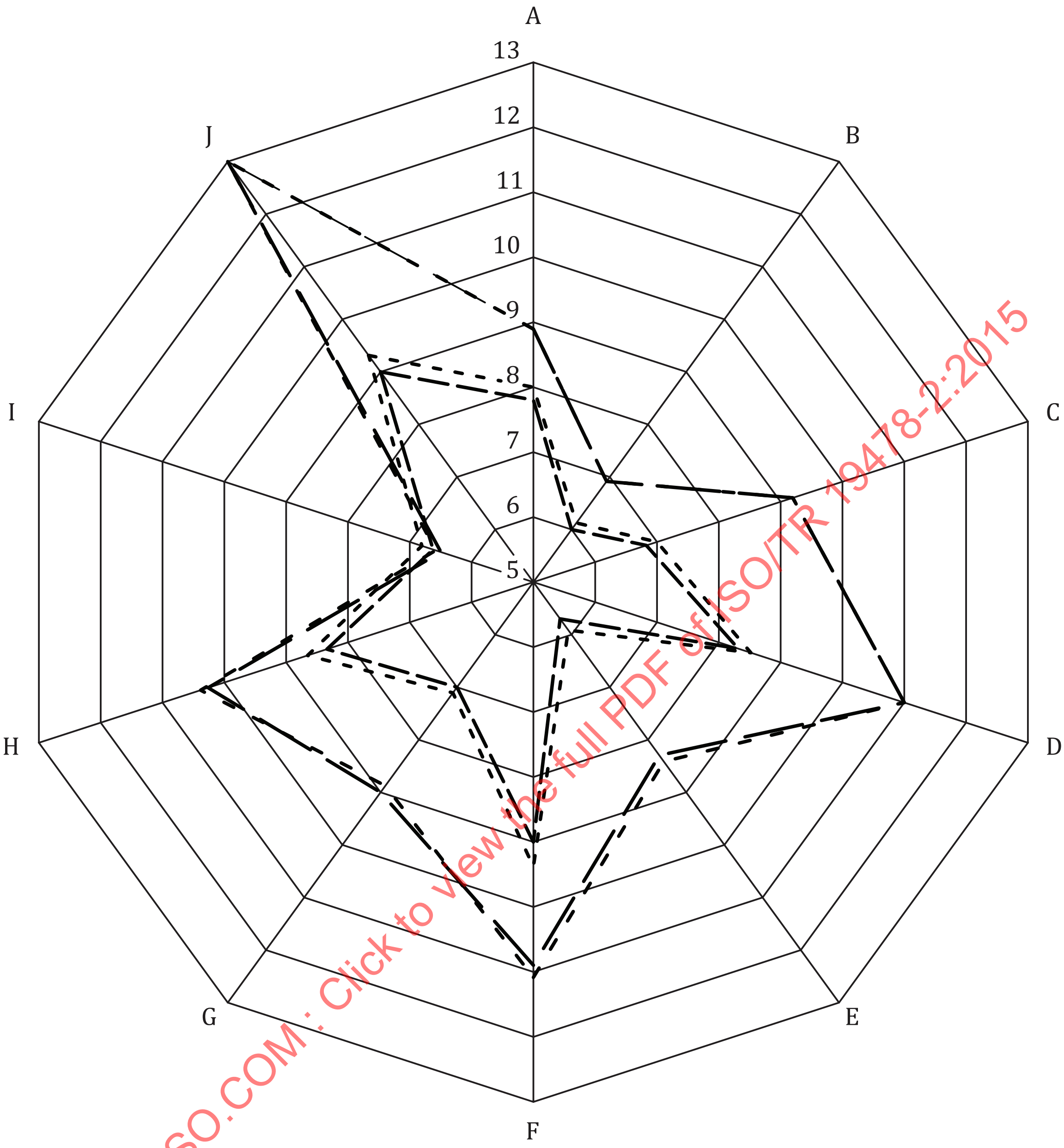
The questions arising from the differences described above are as follows:

a) does the movement of the cigarettes on the rotary machine result in a significant change in puff count by changing the burn rate?

b) does the reaction time of the different termination devices impact significantly on the puff count?

These two questions can be addressed jointly by firstly determining if there is a significant difference in the measured puff number between rotary and linear smoking machines. If a difference in puff number is identified, it is then necessary to establish if it has a significant impact on the measured smoke yield.

The WG 10 study, with the large number of laboratories and almost equal numbers of rotary and linear machines, provides a suitable data set to analyse for differences in puff number. The data was grouped by machine type, rotary and linear, and smoking regime, ISO and HCI, before the procedures of ISO 5725-2 were followed to identify and remove outliers. An analysis was carried out in A.30. The mean values for each machine type and smoking regime are plotted in Figure 29. It is clear that the differences due to machine type are small for both regimes and for all 10 products.



Key

rotary-HCI

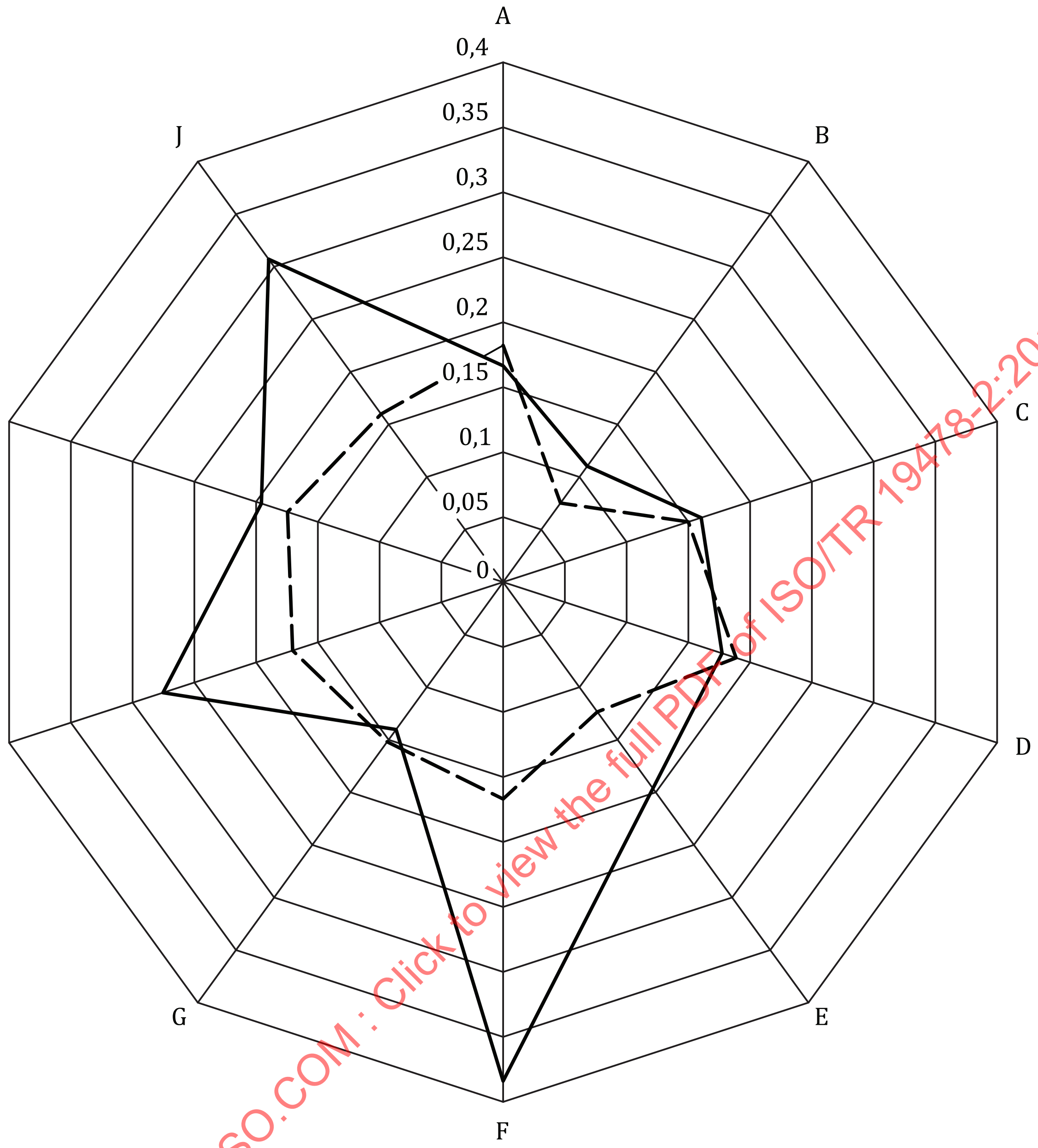
linear-HCI

rotary-ISO

linear-ISO

Figure 29 — Mean puff numbers from rotary and linear machines for products A to J from the WG 10 TNCO study smoked with the ISO and HCI regimes

In order to determine if these small differences were statistically significant, the critical values (the 95 % confidence limit) for the differences were calculated to compare with the measured differences in puff numbers from the two machines. The critical and measured differences for the ISO regime are plotted in Figure 30 and those for the HCI regime in Figure 31. It can be seen from Figure 30 for the ISO regime, that the statistical significance of the machine differences for half of the 10 products is border line while the other half are definitely different. In contrast, Figure 31 shows that the machine differences for the HCI regime are not statistically significant for any of the 10 products.

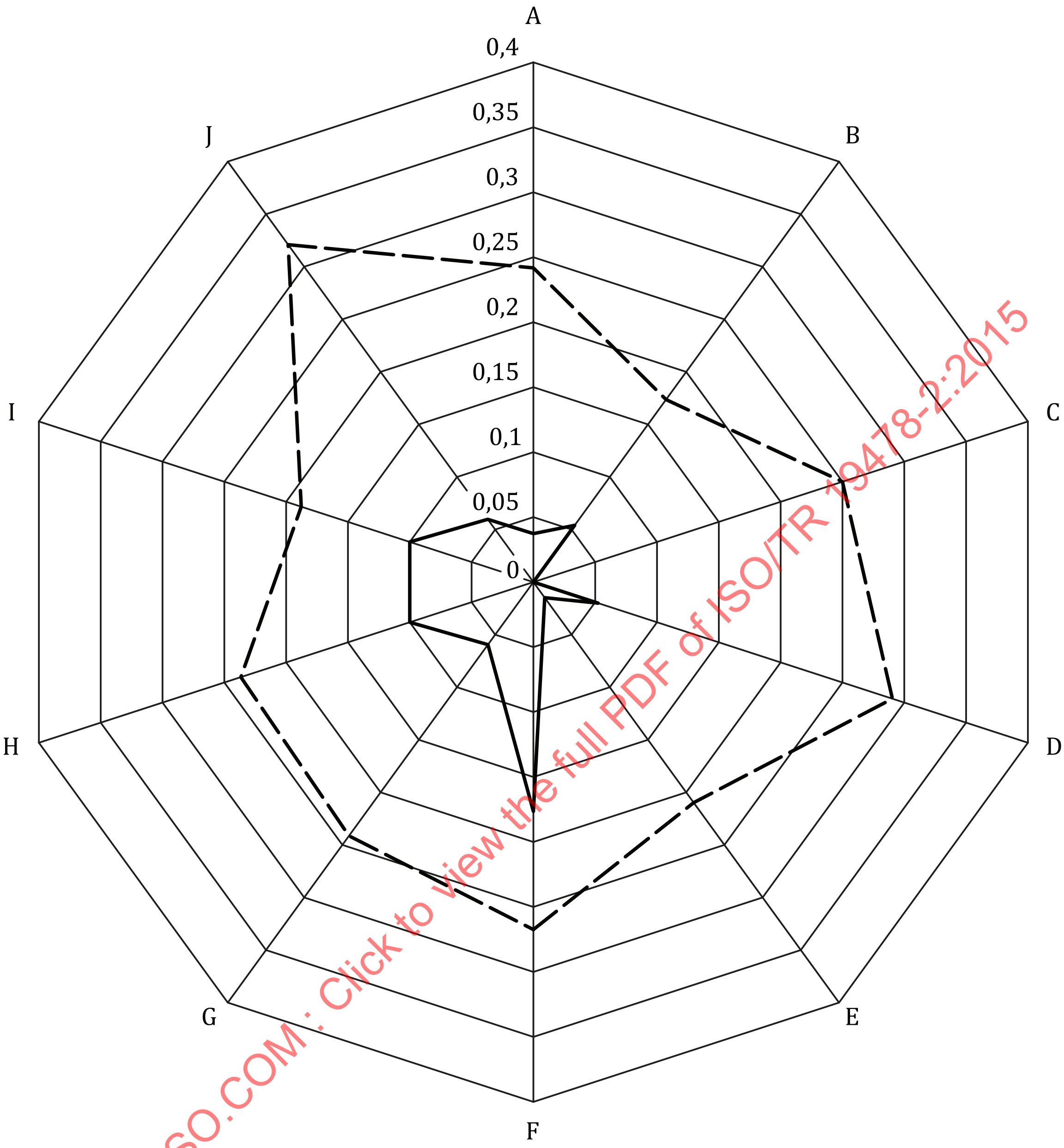


Key

measured-ISO

critical-ISO

Figure 30 — Comparison of the measured difference in puff numbers between rotary and linear machines with the critical differences to indicate statistical significance (Products A to J study from WG 10 TNCO study smoked using ISO regime) (A.30)



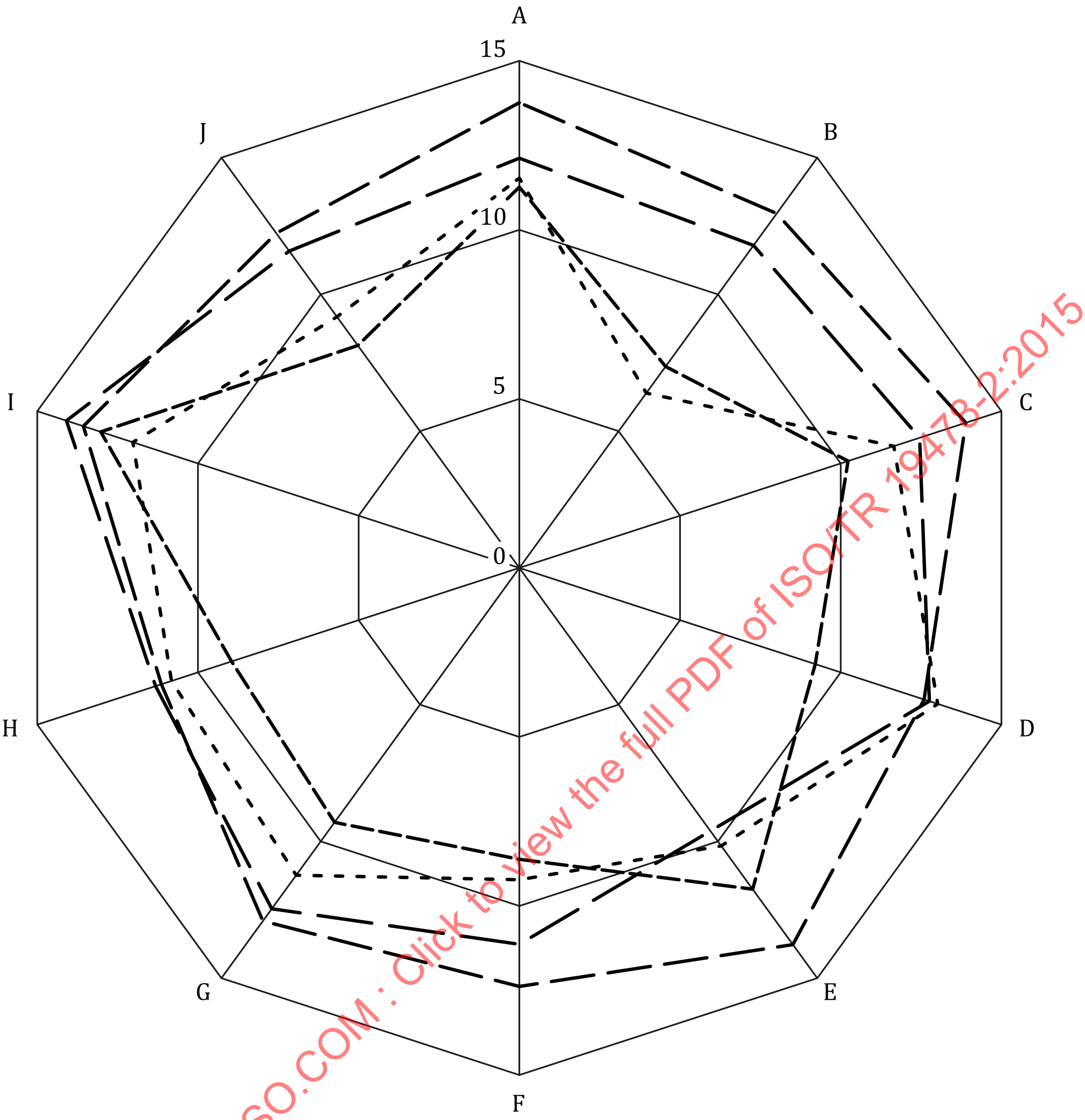
Key

measured-HCI

critical-HCI

Figure 31 — Comparison of the measured difference in puff numbers between rotary and linear machines with the critical differences to indicate statistical significance (Products A to J from WG 10 TNCO study smoked using HCI regime) (A.30)

It is also of interest to compare the two machine types, and hence termination devices, for measurement variability. The reproducibility values for the two machine types and two smoking regimes were calculated and are shown plotted in Figure 32 as the percentage of the mean puff number. The patterns are reasonably circular indicating little difference between the 10 products and the differences between machine types for both smoking regimes are minimal. The values for the ISO regime are, in general, slightly lower but the differences with those using the HCI regime are very small.



Key

- rotary-HCI (long dash)
- linear-HCI (long dash)
- rotary-ISO (dash)
- linear-ISO (short dash)

Figure 32 — Comparison of the reproducibility values for puff number of products A to J from the WG 10 TNCO study as a percentage of the mean value for the rotary and linear machines, and the ISO and HCI regimes (A.30)

The above analysis leads to the conclusions that the differences in puff numbers are small for both regimes, they are not statistically different for the HCI regime and they do not provide a measurable contribution to the yield differences between rotary and linear machines. Although there are some small differences in puff number for the ISO regime, the extremely good agreement in the measured smoke yields rules out the need to try to eradicate them. The reproducibility data indicates that both termination devices are matched in the consistency of the measurements they produce.

6.3 Zone 2: The smoke collection zone

6.3.1 General

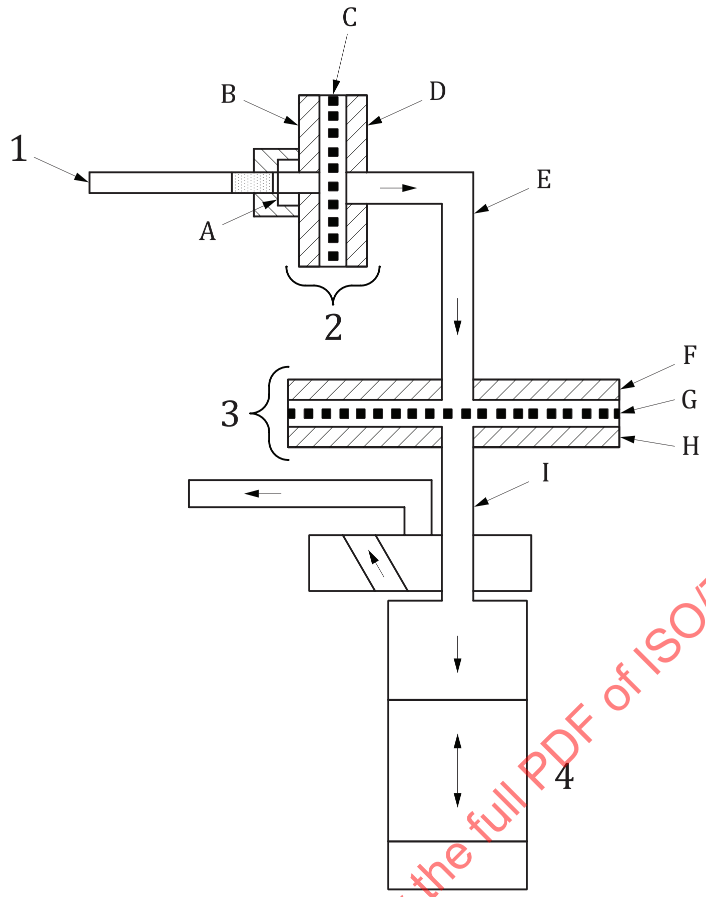
Zone 2 is the smoke collection zone downstream of the cigarette holder which includes the smoke particulate trap and the vapour phase collection bag on the outlet from the puff generator.

6.3.2 Connection of the cigarette holder to the CFH

While the cigarette holder on a linear machine is connected directly to the CFH, the design of the rotary machine makes this impossible and results in the need to have a separate connecting piece. On current designs of rotary machines, this takes the form of a short, low dead volume connecting tube formed into a 90°elbow.

The cigarette holder also needs to hold a soft rubber washer as specified in ISO 3308:2000. Since the CFH is remote from the cigarette holder on the rotary machine, this washer is not included in the gravimetric determination of the TPM yield when weighing the CFH before and after a smoking run. In the case of the linear machine, it is possible to design the cigarette holder/CFH combination with the option of including the washer as an integral part of either of the two components. If the washer is integral with the CFH, it is included in the weight measurements to determine the TPM yield but if it is integral to the cigarette holder it is not. However, the use of CFHs with integral washers on linear machines is considered to be the most frequently used combination.

Tests on an early design of rotary smoking machine A.10 had established that smoke condensate could be deposited before reaching the CFP and not extracted for water and nicotine measurements. Another study (A.22) carried out a more detailed examination of the deposition of smoke condensate in the collection system of current rotary and linear machines. It revealed that a significant amount was deposited in the connector linking the cigarette holder to the CFH on the rotary machine. The tests followed a similar protocol to that reported in 6.2.1 for the A.17 study using a rotary machine capable of two operational modes of smoke collection. The first mode of operation was to use the machine normally (rotary mode) and the second was to place a 44 mm CFH directly behind the cigarette holder so that the TPM collection simulated that of a linear machine (Linear mode). The various components of the smoke collection system (Figure 33) between the cigarette holder and the puffing device were removed from the smoking machine and weighed before and after the smoking run to determine the weight of smoke condensate deposited.



Key

1	cigarette	A	washer
2	44 mm CFH (removed when used in rotary mode)	B	44 mm CFH front
3	92 mm CFH	C	44 mm filter pad
4	puffing device	D	44 mm CFH back
		E	CFH connector
		F	92 mm CFH front
		G	92 mm filter pad
		H	92 mm CFH back
		I	puffing device connector

Figure 33 — Diagram of smoke collection system used for A.22 study

The weights of condensate deposited in the various sections of the smoke collection system, when smoking the CORESTA monitor (CM6), are given in Table 9. It should be noted that the normal procedure for the determination of the TPM yield from a cigarette involves weighing only the CFH, the 44 mm CFH for linear mode and the 92 mm CFH for rotary mode. The normal TPM values in Table 9 are, therefore, those from weighing (F+G+H) for the rotary smoking mode and (A+B+C+D) for the linear mode. The normal TPM yields for the two smoking modes when using the ISO regime are well matched, both about 17 mg/cig, although there is also about 1 mg of condensate deposited in the CFH connector in the rotary mode. The yields for the HCI regime are poorly matched, being about 37 mg/cig for the rotary mode compared with 42 mg/cig for the linear mode. The difference is approximately equal to the amount of condensate deposited in the CFH connector, about 6 mg/cig.

Table 9 — Weight of condensate deposited in sections of the smoke collection system when using the ISO and HCI regimes

HCI regime Deposited smoke condensate (mg/cig)				ISO regime Deposited smoke condensate (mg/cig)			
"Rotary" mode		"Linear" mode		"Rotary" mode		"Linear" mode	
A	0,50	A+B+C+D	42,30	A	0,2	A+B+C+D	17,10
E	5,67	E	0,28	E	1,16	E	0,00
F+G+H	36,61	F+G+H	0,63	F+G+H	16,71	F+G+H	0,19
I	0,46	I	0,40	I	0,26	I	0,01
Total	43,24	Total	44,13	Total	18,13	Total	17,30
Normal TPM yield	36,61		42,30	Normal TPM yield	16,71		17,10

A is the rubber washer.
B is the front of the 44 mm CFH.
C is the 44 mm filter pad.
D is the back of the 44 mm CFH.
E is the CFH connector.
F is the front of the 92 mm CFH.
G is the 92 mm filter pad.
H is the back of the 92 mm CFH.
I is the puffing device connector.

The obvious conclusion from the above observation is that volatile smoke components condense on the internal surfaces of the CFH connector in the rotary mode, for both the ISO and HCI regimes, and this leads to a reduction in the TPM trapped by the CFH. While the amount deposited for the ISO regime is small and has a minor impact on measurements of TPM and NFDPM yields, the amount deposited is greater for the HCI regime and does impact on these yields. To fully understand the significance of these deposits in the CFH connector, it is necessary to know the general composition of the deposited material. Another study (A.26) was set up to establish the proportions of water and nicotine in the deposited smoke condensate.

This study was carried out using a Borgwaldt RM20H® rotary smoking machine to smoke the CM6 monitor cigarette using the HCI regime. The TPM deposited in the CFH, in the CFH connector and on the polychloroprene rubber washer was determined by weighing these items before and after the smoking runs. The TPM collected by the three items was then extracted using isopropanol to determine the water and nicotine content. The agreement between the TPM, water, nicotine and NFDPM measurements from this study and those from the WG 10 study (see Table 10) is very good, indicating the trends in the additional measurements can be assumed to apply to the WG 10 study. It should also be noted that the amount of TPM deposited in the CFH connector, 5,35 mg/cig, is in close agreement with that from the A.22 study, 5,67 mg/cig, given in Table 9 as component E for the HCI regime. The composition of the TPM deposited in the CFH, the CFH connector and on the rubber washer is given in Table 11.

Table 10 — Comparison of A.26 study yields for CM6 with WG 10 study data

	Unit	A.26 study	WG10 study (rotary/CM6)
TPM	(mg/cig)	39,3	39,6
NFDPM	(mg/cig)	27,4	27,3
Water	(mg/cig)	9,28	9,43
Nicotine	(mg/cig)	2,64	2,62

Table 11 — Composition of TPM on CFH, CFH connector and polychloroprene washer

	Unit	CFH	Connector	Polychloroprene washer	Total
TPM	mg/cig	39,3	5,35	0,76	45,4
NFDPM	mg/cig	27,4	1,98	0,32	29,7
	% of TPM	69,7	37,0	42,1	65,4
Water	mg/cig	9,28	3,31	0,43	13,0
	% of TPM	23,6	61,9	56,6	28,6
Nicotine	mg/cig	2,64	0,06	NQ (<0,01)	2,70
	% of TPM	6,7	1,1	0,00	5,9

It can be seen that the TPM deposits on the rubber washer and CFH connector are approximately 60 % water and 40 % NFDPM. The deposition of water is much greater than would be expected from the proportion of water (29 %) in the total TPM collected, indicating that the greater proportion is most probably deposited by condensation from the vapour phase.

The influence of the design of the CFH connector used on the rotary machine was investigated (A.28) in an attempt to identify any design parameters influencing the deposition of TPM. This work included reducing the internal volume of the connector as well as using different materials to manufacture it. While it appeared to be possible to reduce the deposited TPM by reducing the internal volume and switching from metal to glass, the reduction was not associated with an increase in the TPM collected downstream by the CFH. It was also shown to be possible to reduce the deposited TPM by heating the cigarette holder and connector, but again there was no associated increase in the TPM collected by the CFH. These observations are most probably linked to the pattern of the change in the temperature of the smoke during its passage through the CFH connector and CFH and the associated change in the SVD. Consider, for example, that considerably increasing the length of the CFH connector did not increase the TPM deposited. This could be explained by the smoke initially undergoing a rapid cooling close to the entrance to the CFH connector and material condensing onto the walls as the SVD fell, but subsequently both the temperature and SVD stabilizing during the passage of the smoke through the remaining length of the connector so that little, or no, further deposition occurred.

The overall conclusion from the review of the studies above is that the difference in the measured TPM yields between rotary and linear smoking machines is predominantly due to deposition of smoke condensate in the CFH connector on the rotary machine. This deposition also has some influence on the measured water and NFDPM yields.

6.3.3 Collection of TPM and measurement of water and NFDPM

The collection of TPM when using the standards ISO 3308:2000 and ISO 4387 is assumed to take place only in the CFH, although it has been shown in 6.3.2 that, for intense smoking regimes, this assumption is not correct as smoke condensate can be deposited between the cigarette holder and CFH when using the HCI regime with a rotary smoking machine. The basis of the assumption that the particulate phase of cigarette smoke will be trapped with 100 % efficiency in the CFH is found in the specification of the Cambridge filter pad (CFP) in ISO 3308:2000 which specifies the 99,9 % retention of particles of a specified diameter (0,3 µm) similar to that reported for smoke particles. There is also an assumption that the other parts of the CFH will only retain minimal quantities of smoke condensate and ISO 4387 provides procedures, when using the ISO smoking regime, to account for the small proportion of the TPM collected on the internal front surface of the CFH. The efficient trapping of smoke condensate in the CFH to measure TPM relies on the cigarette smoke being a stable aerosol at the ambient temperature (22 °C) of the smoking laboratory and the equipment in it, including the CFH.

The measurement of the NFDPM yield of a cigarette starts with the determination of the TPM yield by weighing the CFH before and after the smoking run. After collecting the TPM, it is necessary to totally extract it from the CFH with a solvent to measure the water and nicotine content. The procedure in ISO 4387 requires the CFH to be opened, the CFP to be removed and placed in solvent, and the inside front surface of the CFH to be wiped with two quarters of a CFP which are also placed in the solvent. This procedure relies on little volatile material being lost between opening the CFH and placing the CFP in the solvent, a low level of deposition on the front CFH internal surface and no deposition on the rear CFH surface. While these conditions apply sufficiently to minimize measurement errors when using the ISO regime, they do not apply for the HCI regime.

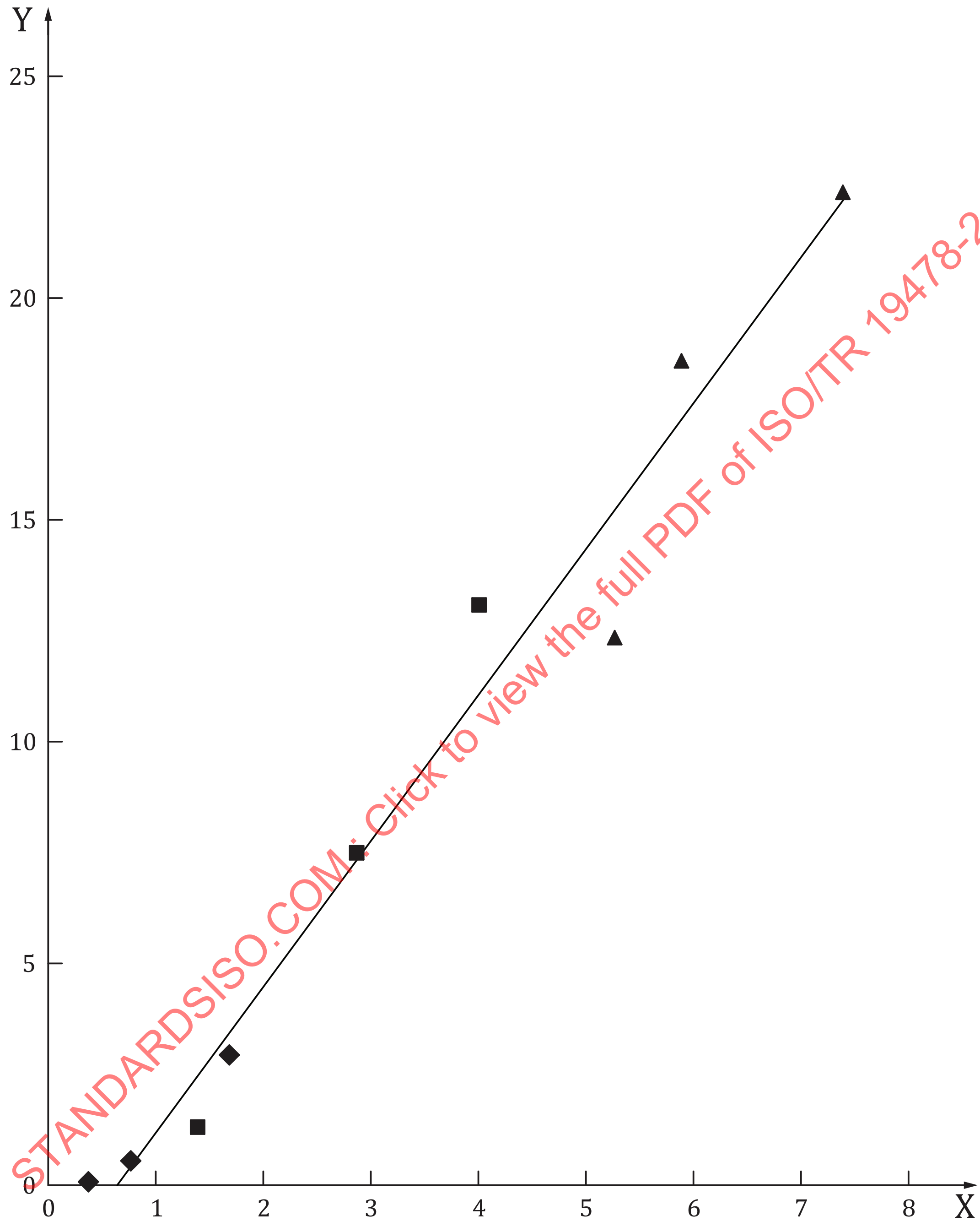
In the A.22 study, the front and back of the 44 mm CFH were weighed independently to determine the amount of condensate deposited during smoking the CM6 monitor using the HCI regime. The TPM deposited on the front and back parts of the CFH was 2,9 % and 1,5 % respectively of the total collected by the CFH. These values are almost certainly lower than the actual amount deposited due to evaporative losses when opening the CFH after the smoking run to weigh its component parts. The vapour phase water measurements in the A.16 study show that the smoke temperature is above the ambient level of 22 °C at the exit of the CFH and is, therefore, still cooling and depositing water through condensation on the surfaces with which it is in contact. Water deposits on the back of the CFH and further downstream of the CFH would, therefore, be expected.

Côté and Verreault[9] (C&V) attempted to reduce the errors in the measurement of NFDPM when using the HCI regime by revising the procedures in ISO 4387 to measure the TPM collected on the filter pad, rather than in the CFH, to calculate the NFDPM yield. This study was also presented to WG 10 at the 8th meeting (A.12). The study compared TPM and NFDPM yields from three products when using the normal ISO 4387 weighing procedure with those obtained when using a modified procedure to weigh the empty CFH and filter pad separately. The results for the TPM measurements are reproduced in Table 12 where it can be seen that the modified method provides consistently lower measurements (12 % to 15 %), and since the water and nicotine yields are the same, the absolute difference in the NFDPM yields is the same as the TPM yields with a greater relative difference (21 % to 25 %). Approximately half of the TPM difference (5 % to 7 %) can be explained by the amount of condensate left in the holder after removing the filter pad and wiping the front surface with the two quarters of a filter pad as specified in ISO 4387. The remaining difference (6 % to 8 %) is assumed to be due to evaporative losses from the filter pad and internal surfaces of the CFH after it is opened.

Table 12 — TPM measurements from A.12 study

Product ISO tar (mg/cig)	TPM method	TPM (mg/cig)	NFDPM (mg/cig)	TPM difference (mg/cig)	Residual mass in CFH (mg/cig)	Unaccounted difference (mg/cig)
2	Standard	35,0	20,7	5,3 (15,1 % of Std)	2,5 (7,1 % of Std)	2,8 (8,0 % of Std)
	Modified	29,7	15,5			
8	Standard	49,3	28,2	5,9 (12,0 % of Std)	2,7 (5,5 % of Std)	3,2 (6,5 % of Std)
	Modified	43,4	22,3			
14	Standard	59,9	34,7	7,4 (12,4 % of Std)	3,4 (5,7 % of Std)	4,0 (6,7 % of Std)
	Modified	52,5	27,3			

Additional measurements were made using the ISO and the Massachusetts regimes. The combined data is shown in Figure 34 where the difference in the TPM yields from the two weighing procedures is plotted against the measured smoke water yield. It is clear that there is a direct proportionality between these two variables indicating that, while the source of the difference is the inefficient extraction of the smoke water collected in the CFH, the magnitude of the TPM difference is driven by the amount of water in the smoke. The study shows that a significant proportion of the smoke condensate collected in the CFH was deposited on the internal surfaces rather than being totally collected on the filter pad, that a substantial proportion of this material was water (>80 %) and a significant proportion was lost, or not extracted, when the CFH was opened. The study supports the findings of the A.22 study which found 4,4 % of the TPM to be deposited on the internal surfaces of the CFH.



Key

X TPM yield difference (mg/cig)

Y measured water yield (mg/cig)

◆ ISO

■ Massachusetts

▲ HCI

Figure 34 — (Cote and Verreault study) — Measured water yield versus TPM yield difference using ISO 4387 and the modified procedure[9]

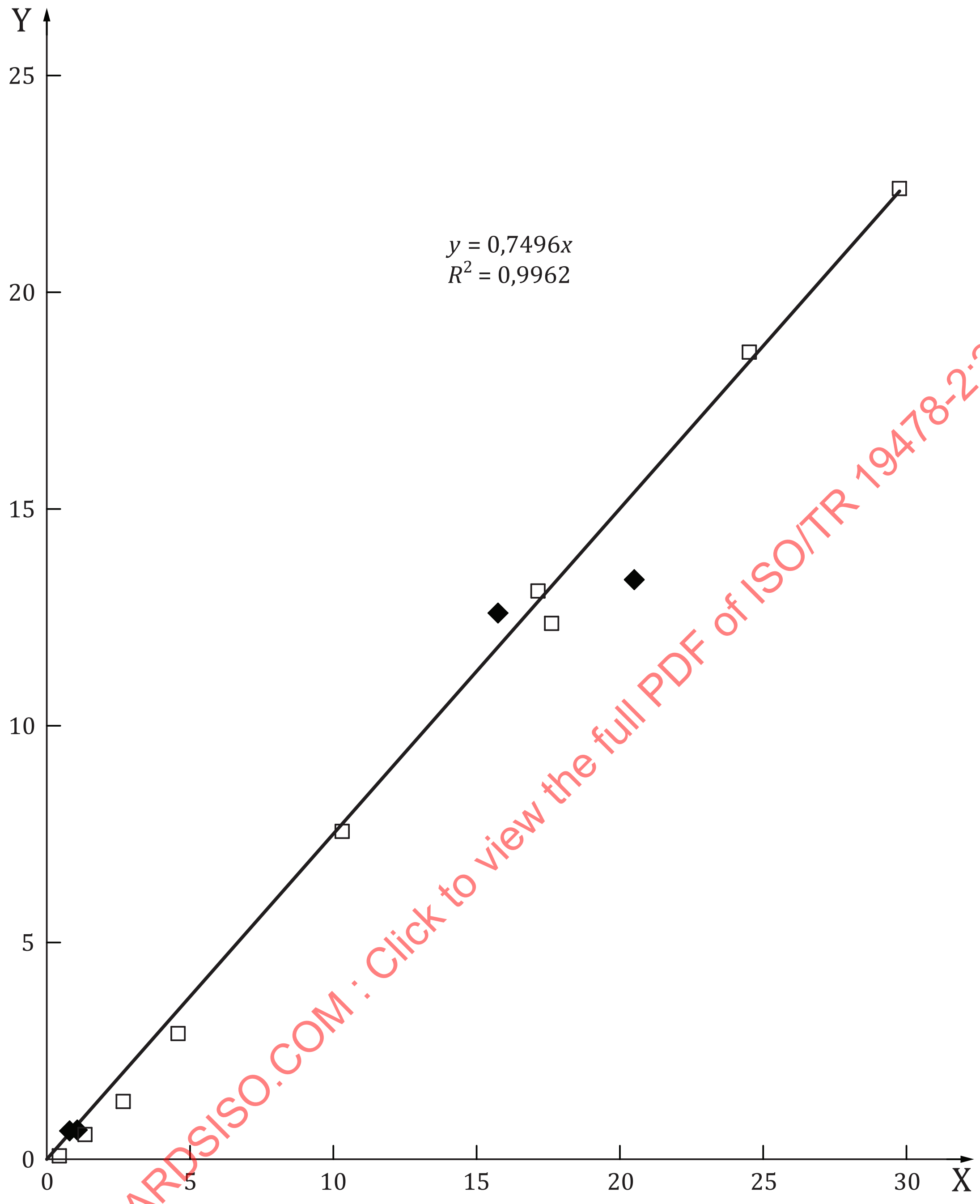
Measurements directly quantifying the loss of water after opening the CFH were presented by Ghosh and Jeannet[10] (G&J). Both the ISO and HCI smoking regimes were used and again the standard procedure from ISO 4387 was compared with a modified procedure for the measurement of TPM, water and NFDPM. The modified "in situ" procedure followed on from weighing the CFH after the smoking run and involved using two syringes to flush 10 ml of isopropanol backwards and forwards through the unopened CFH 60 times over a period of 30 min. The normal ISO procedures were then used to measure the smoke nicotine and water yields.

The study was carried out with three products including the 3R4F reference cigarette and a commercial cigarette. The study used both the ISO and HCI regime and the measurements were based upon 15 determinations for each product (5 cigs/determination for ISO and 2 cigs/determination for HCI). The data for the two cigarette products is given in Table 13. The TPM yields would be expected to be unaffected by the use of different CFH extraction procedures and the agreement between the pairs of measurements for each product type (ISO 4387 extraction procedure and the "in situ") is very good. The agreement in the nicotine measurements is also very good with those from the "in situ" extraction procedure being slightly higher than those from the normal ISO 4387 procedure. This possibly indicates a slightly higher recovery of nicotine from the CFH, although only the 5 % increase for the 3R4F using the HCI regime was found to be statistically significant. The greatest impact of using the "in situ" extraction procedure is the much increased water yields measured when using the HCI regime which results in the corresponding NFDPM yield values being much reduced, the 3R4F by 23 % and the commercial product by 17 %.

Table 13 — Measurements from Ghosh and Jeannet study

	Smoke yields (mg/cig)							
	ISO regime				HCI regime			
	ISO 4387 procedures		"in situ" CFH extraction		ISO 4387 procedures		"in situ" CFH extraction	
	3R4F	Commercial product	3R4F	Commercial product	3R4F	Commercial product	3R4F	Commercial product
TPM	10,46	8,94	10,57	9,06	45,63	39,67	45,85	38,34
Nicotine	0,78	0,64	0,80	0,66	1,97	1,71	2,07	1,75
Water	0,67	0,65	1,14	0,88	13,33	12,58	20,51	15,82
NFDPM	9,01	7,65	8,64	7,54	30,33	25,38	23,27	20,97

The purpose of the measurements both from this study and the C&V study was to provide a direct measure of the true water yield for comparison with that measured using ISO 4387. As the C&V study used an indirect means of doing this, it is of interest to establish the level of agreement with this later study. In order to do this, the "true" water values were calculated for the C&V study by adding the measured difference in TPM to the measured water yields. The "in situ" values were then taken from the G&J study to be the true water yields. These "true" water yields are shown plotted against those measured using the ISO 4387 procedures in Figure 35. The agreement between the two data sets is good and the trend line indicates that measuring the water yield using ISO 4387 procedures underestimates the true yield by about 25 %. This in turn will result in the overestimation of the NFDPM yield when the water yield is subtracted from the TPM yield. While this has a minor impact when using the ISO regime for which the water yield is approximately 10 % of the TPM yield, it has a major impact when using the HCI regime for which the water yield is approximately 40 % of the TPM yield.



Key

X "true" water yield (mg/cig)

Y ISO 4387 water yield (mg/cig)

◆ G&J study

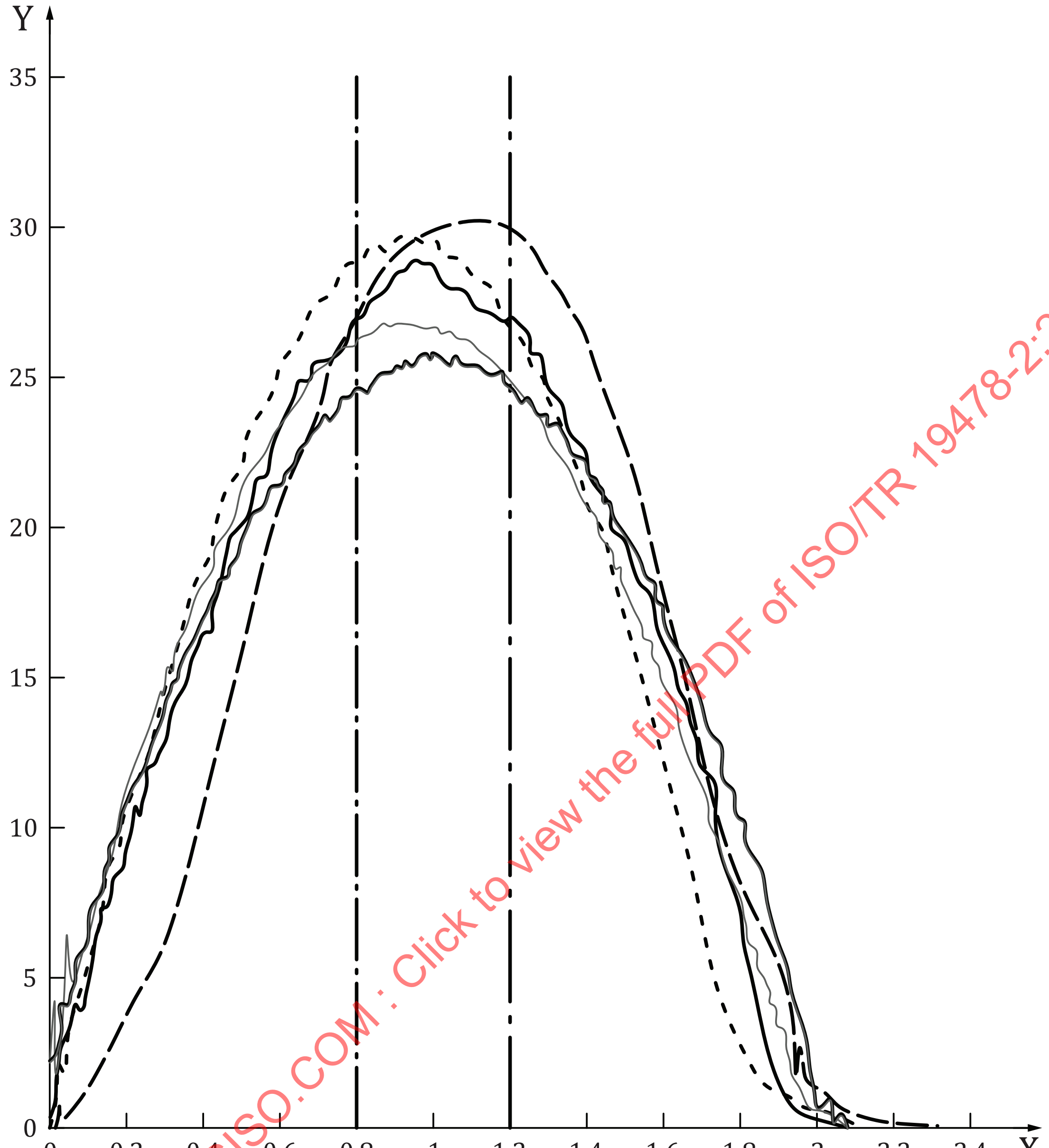
□ C&V study

— linear (both studies)

Figure 35 — Comparison of water yield measurements made by Cote and Verreault (C&V) and Ghosh and Jeannet (G&J)[9,10]

6.4 Zone 3: The puff generator

The puff generator is in the third and final zone of the smoking machine. This piece of the smoking machine is required by ISO 3308:2000 to produce a puff volume of 35 ml over a 2 s period with a symmetrical bell shaped flow profile. The requirement for a bell shaped profile is based upon the historical use of a piston moved by a rotating crank to draw the required puff volume through the cigarette being smoked. Three design options for such a system are shown in ISO 3308:2000, Annex B, each of which would produce a different shape for the bell profile. Examples of profiles obtained on five commercially available smoking machines, of rotary and linear design, from four manufacturers were presented by Mason[11] as a poster presentation at the CORESTA meeting in 2004 and are reproduced in Figure 36. While there are obvious differences in the profiles, all were set to provide a 35 ml puff volume and satisfy the flow characteristics specified in ISO 3308:2000, 4.5, given below.



Key

X   time (s)

Y   flow (ml/s)

—— · —— 0,8 s

—— - —— 1,2 s

- - - - - - - machine A

———— machine B

———— machine C

———— machine D

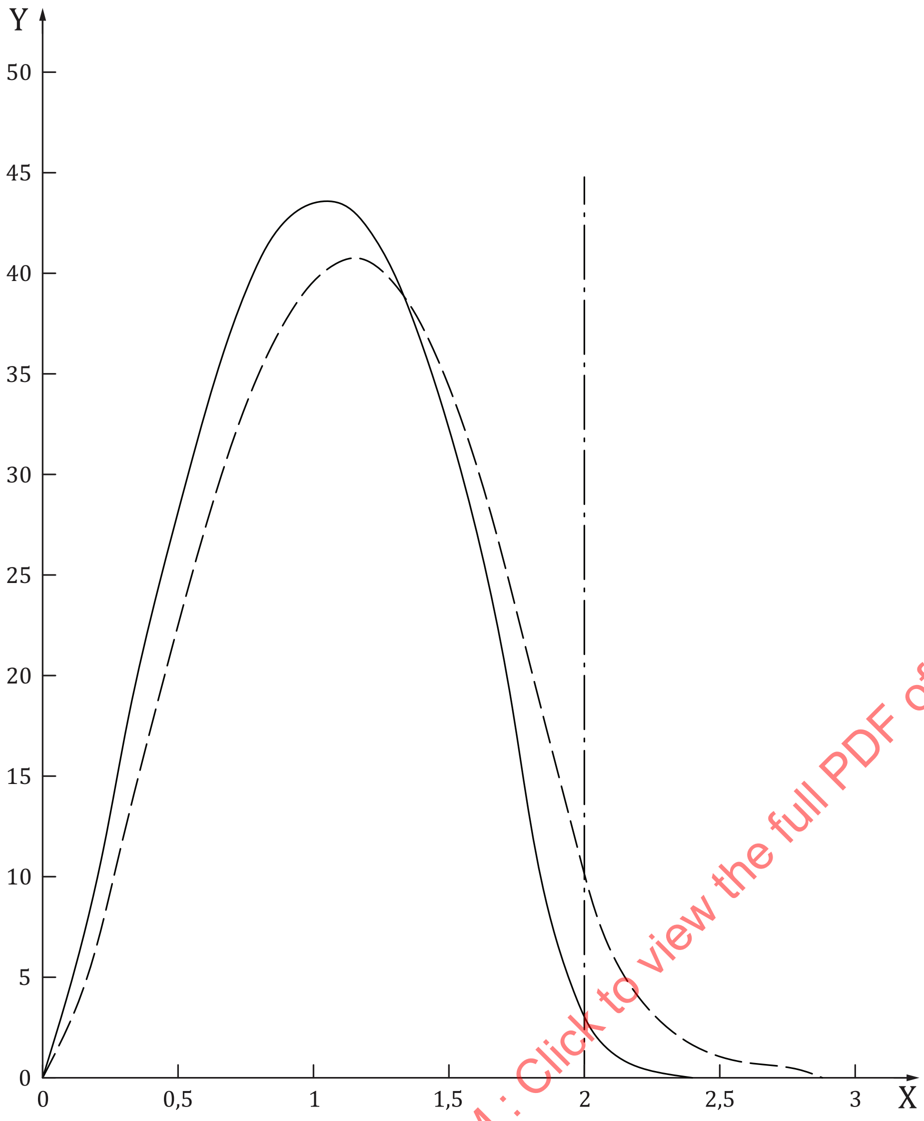
— — — — machine E

Figure 36 — Puff profile measurements from five commercial smoking machines with the volume set to 35 ml[11]

ISO 3308:2000, Annex C illustrates how the bell profile will be distorted when an additional flow resistance such as a cigarette is introduced in front of the puff generator. The flow through the cigarette will lag behind the volume being displaced at the piston with a consequent reduction in the pressure at this point resulting in a distortion of the original bell profile including delaying the profile reaching a peak value. Additionally, the pressure in the piston will still be below atmospheric pressure after 2 s when the puff is terminated by closing the connection to the cigarette resulting in a reduction in the volume drawn through the cigarette. This consequence is also illustrated in ISO 3308:2000, Annex C. Measured puff profiles are also shown in Figure 37 for a rotary smoking machine with the puff volume set to 55 ml and the duration to 2 s. The profile is measured with zero flow resistance added at the cigarette holder and with 3 kPa of additional flow resistance at the cigarette holder. Figure 37 shows the same distortion in the flow profile as indicated in ISO 3308:2000, Annex C and indicates how the volume will be reduced by the loss of the rear end of the puff after the set 2 s puff duration.

Table 14 — Puff volume and peak flow checks on a rotary smoking machine using a 3 kPa resistor

Set volume ml	Measured volume ml	Reduction ml	Reduction %	Time to peak flow s
35	33,6	1,4	4,0	1,10
55	51,8	3,2	5,8	1,12



Key

X time from start of puff (s)

Y flow rate (ml/s)

——— 0 kPa

— — — 3 kPa

— - — 2 s

Figure 37 — Puff profile measurements on a rotary smoking machine with the volume set to 55 ml and the duration to 2 s (A.31)

ISO 3308:2000 sets limits for the permissible reduction in puff volume due to a specified increase in the flow resistance at the cigarette holder as well as limiting the movement of the position of the maximum flow rate from the midpoint of the puff.

Under ISO 3308:2000, Clause 4,

Subclause 4.3 requires that *"The standard puff volume measured in series with a pressure drop device of 1 kPa ± 5 % shall be (35,0 ± 0,3) ml. In one puff duration not less than 95 % of the puff volume shall leave the butt end of the cigarette."*

And,

Subclause 4.5 requires that *"The puff profile shall be measured with an impedance of 1 kPa ± 5 % as specified in 4.3. It shall be bell-shaped with a maximum between 0,8 s and 1,2 s from the start of the puff.*

The increasing and decreasing parts of the profile shall not have more than one point of inflection each. The maximum flow rate shall be between 25 ml/s and 30 ml/s (see Annex B). At no point shall the direction of flow be reversed."

Under ISO 3308:2000, 5.3 *Reliability and compensation*,

Subclause 5.3.3 requires that *"The machine shall be capable of sufficient compensation (see 3.18). When the machine has initially been set to give a puff volume of 35 ml without a pressure drop device, a reduction of no more than 1,5 ml shall be observed when the machine is tested with a pressure drop device of 3 kPa."*

Since the requirements of the above causes are met by the design of the smoking machine, the checks for compliance with ISO 3308:2000 are carried out by the manufacturers of the smoking machines. It is not possible to determine if alternative smoking regimes to the ISO regime comply with ISO 3308:2000 because the checks in ISO 3308:2000 are specific to the ISO smoking regime. It is, however, possible to assess the reduction in puff volume and displacement of the position of the maximum flow using similar procedures, and such measurements have been carried out (A.31).

The procedure in ISO 3308:2000, 5.3.3 was used to measure the puff volume drawn over a two second period with a flow resistance of 3 kPa (measured at a flow of 17,5 ml/s) in front of the puff generator and the volume set to be 35 ml or 55 ml without the flow resistor. The measurements in Table 14 show that the reduction in puff volume increases from 4 % at 35 ml to 5,8 % at 55 ml. While the reduction is greater for the 55 ml puff volume, the increase is not sufficient to cause concern when considering its potential impact on the measurement of smoke yields. The measured times to the peak flow for the two puff volumes in Table 14 are very similar and within the range specified in ISO 3308:2000, 4.5.

The measurements in Table 14 are considered to be representative of smoking machines in general and indicate that they are capable of drawing a puff volume of up to 55 ml without serious distortion to the puff profile. It should be noted, however, that when smoking cigarettes, this conclusion applies when the flow resistance of the smoke trap is under 3 kPa and remains constant during puffing. The standard CFP for trapping smoke particulates is cut from a material providing low flow resistance and is held in the CFH which is designed to provide an overall low flow resistance in combination with the CFP. When using liquid traps, the design specification should include the requirement to minimize the flow resistance of the trap and avoid distortion of the puff profile. Mason[11] also considered these issues pointing out that a single tube liquid trap grossly distorted the puff profile whereas the use of a sintered disc largely prevented such distortion by breaking up the smoke flow through the liquid into smaller elements. He also warned that the use of a sintered disc could greatly increase the flow resistance of the trap which in turn would produce a tail on the puff profile, as shown in Figure 37, and so reduce the puff volume when this was cut off at the end of the 2 s puff.

7 Overall summary

This part of ISO/TR 19478 covers a number of independent studies dealing with a range of issues associated with using smoking regimes of a much greater intensity than specified in ISO 3308:2000. When the conclusions from these independent studies are combined, they provide a general understanding of the limitations of using procedures and equipment specified in the current ISO standards for cigarette smoking with intense smoking regimes. The clauses of this part of ISO/TR 19478 providing the detailed discussions leading to the processes described below are indicated in brackets.

The temperature of the smoke passing out of a cigarette is dependent upon the smoking intensity and increases as the puff volume and puff frequency are increased (5.3). The SVD of water is extremely sensitive to changes in temperature and increases rapidly with the temperature (5.4). This enables the smoke vapour phase from an intense smoking regime to carry a much increased quantity of water until it cools in the collection system and the water condenses onto available surfaces (5.5).

The Cambridge filter pad, and the associated Cambridge filter holder, is specified (ISO 3308:2000) for the sole purpose of collecting smoke TPM as particulate material and does this efficiently for the ISO smoking regime. Its use with the HCI regime is compromised by the greatly increased SVD which requires the trapping of a much increased level of smoke vapour phase water for which liquid traps are more suited.

