Report No. 411289 / 2
Air Pollution / Environmental Technology Laboratory

Your research and test laboratory

Ordered by:

Swiss Agency for the Environment, Forests and Landscape (SAEFL)
Air Pollution Control Division

3003 Bern

Emissions Measurements on CRT-Equipped City Buses on the LARAG AG Chassis Dynamometer Test Bench in Wil

from 28 – 30 March 2000

Revised August 2004

Dübendorf, 2 August 2004

EMPA Dübendorf
Air Pollution / Environmental Technology Laboratory

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Contents

1 Summary

The exhaust gases from 3 city buses equipped with CRT (continuously regenerating trap) systems were analysed on the LARAG AG chassis dynamometer test bench in Wil from 28 to 30 March 2000. One bus was operated with two fuel qualities with sulphur contents of 10 and 50 ppm, respectively. Each vehicle was operated on an ESC cycle (European Stationary Cycle) with 13 steady-state modes. This report summarizes the results from the continuous measurement of gaseous substances performed by EMPA.

The gases measured were various nitrogen oxides (N_2O, NO, NO_2, NO_x), as well as VOC and CO. An average was calculated for each of the 13 steady-state conditions. In addition, several modes (n = 2 – 5) were also sampled upstream of the CRT system for each cycle in order to estimate the corresponding emissions without the CRT.

Special consideration was given to the determination of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Sampling was undiluted using a heated filter and Teflon tubing. Water was eliminated using a permeation dryer. As opposed to condensating systems, this does not induce any losses due to the high solubility of NO_2 in water. The analysis was performed using a 2-channel chemiluminescence analyser.

In addition to the reduced particle emissions, which will be discussed in a separate report by Matter Engineering (Wohlen), use of the CRT system also results in a significant decrease in concentrations of VOC and CO. If the values from the measurements upstream and downstream of the filter are compared, the reduction in VOC levels is between 72% and 98%, while that for CO is between 65% and 99%.

N_2O concentrations were always below 3.4 ppm, considerably less than 1 percent of the emitted NO_x. N_2O concentrations downstream of the CRT were always slightly higher, the largest increase being 1.4 ppm.

As can be anticipated, the NO_x concentration was highest (max. 2030 ppm) at each speed in full load operation. In contrast, NO_2 concentrations were highest (max. 470 ppm) at 25% and 50% load. This means that NO_x concentrations decrease with decreasing load while the concentration of NO_2 increases. This can be attributed to the fact that the oxidation of NO to NO_2 becomes more significant at lower load, in several cases resulting in a more than 70% fraction of NO_2 with respect to NO_x. Because of efficient NO oxidation at low load and high NO production at high load, the highest NO_2 concentrations were usually observed at 50% load.

From the measurements upstream and downstream of the filter, it is clear that the NO_2 emissions at loads below 50% can be attributed primarily to the exhaust gas treatment and not to the direct emissions from the combustion engine. In addition, the NO_2/NO_x ratio decreased nearly linearly with increasing temperature. This indicates that temperature is a significant parameter in the generation of NO_2 from NO_x in the CRT system.

2 Introduction

With its order of 3 April 2000, based on the quotation of 20 March 2000, the SAEFL contracted EMPA to perform emission measurements on CRT-equipped city buses on LARAG AG's chassis dynamometer in Wil.

The following aspects were to be evaluated with regard to the effect of the CRT by means of ESC (European Stationary Cycle) measurements on 3 buses:

- Nitrogen oxides (especially the ratio of NO_2 to NO)
- Particulate matter
- Effect of fuel sulphur content on operating behaviour of the CRT.

EMPA (Air Pollution/Environmental Technology Laboratory) was responsible for continuous measurement of the gaseous emissions, while determination of particulate matter was performed by Matter Engineering in Wohlen. One vehicle was operated with two diesel qualities (sulphur content approx. 10 and 50 ppm) in order to evaluate the effect of sulphur content on the operating behaviour of the CRT. The measurement program was provided by UMTEC (Rapperswil). Further evaluations of the data discussed here are planned by TTM (Niederrohrdorf) and UMTEC. This report contains only the measurements performed by EMPA.

3 Instrumentation

MEASUREMENT METHODS AND PROCEDURES

When appropriate, the measurement methods listed in the "Recommendations for emissions measurement of air contaminants in stationary facilities" of the Swiss Agency for the Environment, Forests and Landscape (SAEFL) of 25 January 1996 were used.

Unless otherwise indicated, all concentration data in this report are based on dry exhaust gas at standard conditions (0°C and 1013 mbar). Methods and equipment are described below.

Exhaust gas temperature	Thermoelectric, continuous Wick Numatron type 90
Sampling	Heated filter, 120°C, Koneth; heated Teflon line, 120°C, 5 m, Winkler; permeation dryer PD-750-48-55, Perma Pure INC/Koneth; unheated PTFE lines (shorter than 5 m) are used from permeation dryer to analyser
Oxygen	Susceptibility measurement, continuous; Servomex 570 A, 0 – 100% O_2
Nitrogen oxides	Chemiluminescence, continuous; Eco-Physics CLD 700 EL ht, 0-10000 ppm NO, 0-10000 ppm NO_x
N_2O	NDIR gas filter correlation, cont.; TEI 46, 0 – 100 ppm N_2O
Carbon monoxide	NDIR absorption, cont.; Maihak UNOR 600, 0 – 1000 ppm CO
Volatile organic compounds	Heated filter, 120°C, Koneth; heated Teflon line, 120°C, 5 m, Winkler; flame ionization detector, continuous; J.U.M. VE5, 0 – 1000 ppm C_3H_8

Calibration of gas analysers

Zero and span were determined using the certified calibration gases given in Table 1.

Table 1: Calibration gases

Calibration gas	Concentration	Manufacturer	Last check of concentration
NO	902 ppm	Carbagas	08/98
N_2O	90.0 ppm	Carbagas	09/99
CO	900 ppm	Carbagas	07/99
C_3H_8	900 ppm	Carbagas	08/99
N_2		Carbagas	-

Uncertainty

The measurement uncertainties given are the 95% confidence intervals based on the complete measuring technique, i.e. sampling, sample processing and analysis.

Table 2: Measurement uncertainty and detection limits

Parameters	Measurement uncertainties for individual values		Detection limit
Physical parameters			
Exhaust gas temperature	3%		
Reference parameters			
Oxygen (O_2)	5%		
Pollutants			
Nitrogen oxides (NO_x)	10%	minimum 2 mg/m^3	2 mg/m^3
Dinitrogen oxide (N_2O)	10%	minimum 0.5 mg/m^3	0.5 mg/m^3
Carbon monoxide (CO)	10%	minimum 5 mg/m^3	2 mg/m^3
Volatile organic compounds (VOC)	10%	minimum 2 mg/m^3	2 mg/m^3

4 Measurement Program

Dates

28 to 30 March 2000

Location

LARAG AG chassis dynamometer test bench in Wil.

Part of the exhaust gas flow was extracted downstream or upstream of the vehicles' CRT systems and the concentrations measured undiluted after sample preparation.

PARAMETERS

Physical parameters	-	Exhaust gas temperature
Reference parameters	-	Oxygen (O_2)
Pollutants	-	Nitrogen oxides (NO_x, NO, NO_2, N_2O)
	-	Carbon monoxide (CO)
	-	Volatile organic compounds (VOC)

VEHICLE OPERATING CONDITIONS

Each vehicle was operated at the 13 steady-state modes of the ESC cycle (European Stationary Cycle). Buses No. 1 and 2 are the same vehicle, operated with different fuels. The numbering system is given in Table 3.

Table 3: Vehicle data and sulphur content of diesel fuel

Bus No.	Registration	Test designation	S content in diesel [ppm]	Filter type
1	SG 3309	Halter Volvo 50 ppm	50	Eminox
2	SG 3309	Halter Volvo 10 ppm	10	Eminox
3	ZH 540689	VBZ HJS	10	HJS
4	SG 221820	Halter NAW	30	Eminox

MEASUREMENT

For each mode, a 2-minute average was determined after constant concentrations had been reached (5-10 min). These average values are given in the following tables and plots. Some ESC modes were also sampled upstream of the CRT using identical measurement procedures.

5 Results

The detailed results for all vehicles are presented in the tables and figures in Appendices 1 (overview) and 2 (nitrogen oxides).

All of the continuously measured values are listed in Tables 4 - 7. They include the values with CRT for all modes and measured substances. In addition, the measurements upstream of the CRT (n = 2 – 5) give a rough estimate of the emissions of the corresponding diesel engines without CRT.

The overview clearly illustrates that the CRT system results in a pronounced decrease in VOC and CO concentrations. If the values from the measurements upstream and downstream of the CRT are compared, the reduction of VOCs lies between 72% and 98%, while that for CO is between 65% and 99%.

N_2O concentrations were always below 3.4 ppm, considerably less than 1 percent of the emitted NO_x. N_2O concentrations downstream of the CRT are always slightly higher, the largest increase being 1.4 ppm.

NO_2 concentrations increased significantly by the CRT system. This increase is strongly dependent on the load (cf. Appendix 2). NO_2 emissions increased by a factor of 2 to 7, depending on vehicle and operating conditions.

Appendix 2 contains various graphical presentations of the measured nitrogen oxide concentrations. NOx and NO_2 are plotted in Figures 1 to 4 for the four tested vehicles.

As anticipated, NO_x concentration was highest for each speed at 100% load and decreased with decreasing load. The greatest concentration was measured for vehicle No. 4 at full load (2030 ppm).

In contrast, NO_2 concentrations were highest at 25% and 50% load. The highest value (470 ppm) was measured for vehicle No. 3 at 50% load and 1300 rpm. NO_x concentrations decrease with decreasing load while the concentration of NO_2 increases. This can be attributed to the fact that the oxidation of NO to NO_2 becomes more significant at lower load, in several cases resulting in a more than 70% fraction of NO_2 with respect to NO_x.

Because of efficient NO oxidation at low load and high NO production at high load,, the highest NO_2 concentrations usually occur at 50% load (Fig. 6). The good agreement between data sets 1 and 2 is also clear in Figs. 5 and 6. These data were measured for the same bus on different days and with different fuel (sulphur content 10 or 50 ppm).

Figs. 7 and 8 summarize all of the modes in which measurements were made both upstream and downstream of the CRT. The data clearly show that the observed high NO_2 concentrations at loads below 50% can be attributed primarily to the CRT system and not to the emissions directly from the combustion engine. In contrast to this, the oxidation of NO at full load is much less pronounced and does not result in pronounced NO_2 concentrations under these conditions, despite the high NOx concentrations

The relationship between load and the fraction of NO_2 indicates that temperature could be the decisive parameter. The NO_2/NOx ratio is therefore plotted against exhaust gas temperature in Fig. 9. This plot accounts only for values determined with the CRT and which are not disturbed by changeovers between sampling upstream or downstream of the CRT. The sections between the steady-state phases were also sampled in many cases. As a result, data are usually available not only for the discrete modes, but rather over the entire temperature range.

Fig. 9 shows that the NO_2/NOx ratio decreased nearly linearly with increasing temperature. This dependence would merit a more detailed study in the CRT system. It appears to be determined primarily by the oxidation of NO on the catalyst and the uptake of NO_2 by the particle filter, both of which processes are temperature-dependent.

Appendix 1 – Overview of measurement results

Table 4: Overview of data from vehicle No.1

Test designation:	Halter Volvo 50 ppm
Rigistration:	SG 3309
Diesel S content:	50 ppm
Date:	28.03.2000

rpm	Load	upstr. of filter	N_2O [ppm]	NO_x [ppm]	NO [ppm]	NO_2 [ppm]	C_3H_8 [ppm]	CO [ppm]	O_2 [%]	Temp. [°C]	NO_2/NO_x [%]	Δ C_3H_8 [%]	Δ CO [%]
Idle	0		1.5	439	427	19	36	11	16.5	112	4		
2400	100		1.4	656	537	123	7	23	10.2	357	19		
2400	75		1.3	560	341	226	8	13	12.2	303	40		
2400	50		1.3	530	328	209	10	12	12.8	302	39		
2400	25		1.3	419	250	175	11	7	13.8	268	42		
1900	100		1.3	647	558	95	6	24	10.0	396	15		
1900	75		1.2	559	416	148	7	22	11.1	331	26		
1900	50		1.4	843	521	328	6	22	11.6	313	39		
1900	24		1.4	646	335	318	6	11	12.8	276	49		
1400	100		2.6	1083	1002	89	8	40	7.2	356	8		
1400	75		1.3	1023	891	139	4	36	8.1	357	14		
1400	50		1.3	883	661	230	4	31	9.5	335	26		
1400	25		1.4	583	261	330	4	13	11.9	274	57		
2400	100	X	1.2	642	616	33	30	86	10.5	389	5	77	73
1400	25	X	1.1	677	655	28	51	85	11.6	314	4	92	85

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Table 5: Overview of data from Vehicle No.2

Test designation: Halter Volvo 10 ppm
Rigistration: SG 3309
Diesel S content: 10 ppm
Date: 30.03.2000

rpm	Load	upstr. of filter	N_2O [ppm]	NO_x [ppm]	NO [ppm]	NO_2 [ppm]	C_3H_8 [ppm]	CO [ppm]	O_2 [%]	Temp. [°C]	NO_2/NO_x [%]	Δ C_3H_8 [%]	Δ CO [%]
Idle	0		1.8	438	411	33	27	6	16.7	122	8		
2400	100		1.5	652	541	117	6	25	10.5	373	18		
2400	75		1.8	556	354	209	7	15	12.2	328	38		
2400	50		1.5	501	298	210	12	10	13.0	299	42		
2400	25		1.6	400	223	183	14	6	14.0	262	46		
2400	25	X	1.5	402	367	43	60	78	14.0	260	11	77	93
1900	100		1.4	584	468	122	6	23	10.7	357	21		
1900	75		1.4	540	385	162	6	18	11.4	336	30		
1900	50		1.6	777	421	364	7	15	11.9	289	47		
1900	25		1.8	602	285	324	8	7	13.2	249	54		
1400	100		1.5	1032	939	100	5	33	7.4	375	10		
1400	100	X	1.4	1023	993	35	49	144	7.4	376	3	91	77
1400	75		1.5	925	742	191	5	27	8.4	341	21		
1400	50		1.5	748	461	295	4	19	10.0	295	39		
1400	25		1.8	494	187	312	5	8	12.5	244	63		
1400	25	X	1.5	564	520	53	62	120	12.4	230	9	92	93

Table 6: Overview of data from Vehicle No. 3

Test designation:	VBZ HJS
Rigistration:	ZH 540689
Diesel S content:	10 ppm
Date:	29.03.2000

rpm	Load	upstr. of filter	N_2O [ppm]	NO_x [ppm]	NO [ppm]	NO_2 [ppm]	C_3H_8 [ppm]	CO [ppm]	O_2 [%]	Temp. [°C]	NO_2/NO_x [%]	Δ C_3H_8 [%]	Δ CO [%]
Idle	0		1.2	289	281	13	48	125	17.9	124	4		
2200	100		2.7	1394	1343	60	6	348	4.4	572	4		
2200	100	X	1.7	1353	1289	73	22	> 1000	3.9	536	5	72	65
2200	75		1.6	1284	1227	65	3	34	7.6	509	5		
2200	50		1.5	984	788	204	3	16	10.6	421	21		
2200	25		1.7	649	333	324	4	8	12.9	346	50		
2200	25	X	1.5	734	636	103	53	191	12.5	340	14	93	96
1800	100		2.2	1517	1442	83	3	138	4.1	570	5		
1800	75		1.7	1313	1186	134	2	19	8.0	470	10		
1800	50		1.5	878	500	385	3	6	11.3	377	44		
1800	25		1.9	509	134	382	4	3	14.0	293	75		
1300	100		2.1	1604	1506	106	0	37	4.1	508	7		
1300	100	X	1.3	1019	972	54	6	> 1000	8.7	543	5	96	96
1300	75		1.7	1417	1182	244	0	35	8.6	417	17		
1300	50		1.7	846	380	474	0	10	11.8	328	56		
1300	25		3.4	511	117	399	3	3	14.5	255	78		
1300	25	X	1.4	640	470	176	118	336	14.2	245	28	98	99

Table 7: Overview of data from Vehicle No.4

Test designation: Halter NAW
Rigistration: SG 221820
Diesel S content: 30 ppm
Date: 29.03.2000

rpm	Load	upstr. of filter	N_2O [ppm]	NO_x [ppm]	NO [ppm]	NO_2 [ppm]	C_3H_8 [ppm]	CO [ppm]	O_2 [%]	Temp. [°C]	NO_2/NO_x [%]	Δ C_3H_8 [%]	Δ CO [%]
Idle	0		1.5	267	253	20	17	49	18.2	141	7		
2200	100		2.3	1969	1795	184	4	80	8.5	495	9		
2200	100	x	1.8	1872	1699	183	69	238	9.0	462	10	94	67
2200	75		2.1	1566	1320	255	5	54	10.1	444	16		
2200	50		1.9	1039	724	323	6	35	11.6	385	31		
2200	25		1.8	581	282	307	5	17	13.3	325	53		
2200	25	x	1.5	631	545	91	73	132	13.3	320	14	93	87
1800	100		1.9	2000	1743	268	4	55	8.3	477	13		
1800	75		1.7	1380	1010	380	4	34	10.2	409	28		
1800	50		1.7	873	473	406	4	19	11.8	351	47		
1800	25		1.8	490	177	319	4	9	13.7	301	65		
1300	100		2.1	2030	1802	238	3	52	5.7	481	12		
1300	100	x	1.3	2050	1901	160	40	782	5.6	502	8	93	93
1300	75		1.9	1751	1416	345	5	39	7.8	429	20		
1300	50		1.7	1031	578	460	3	21	10.7	348	45		
1300	50	x	1.4	1104	995	117	49	96	10.9	337	11	93	79
1300	25		2.7	471	123	355	4	4	13.9	243	75		
1300	25	x	1.4	593	505	93	54	149	13.9	276	16	93	97

Appendix 2 – Nitrogen oxides

Fig. 1: Nitrogen oxide concentrations from vehicle No.1 (SG 3309, 50 ppm S)

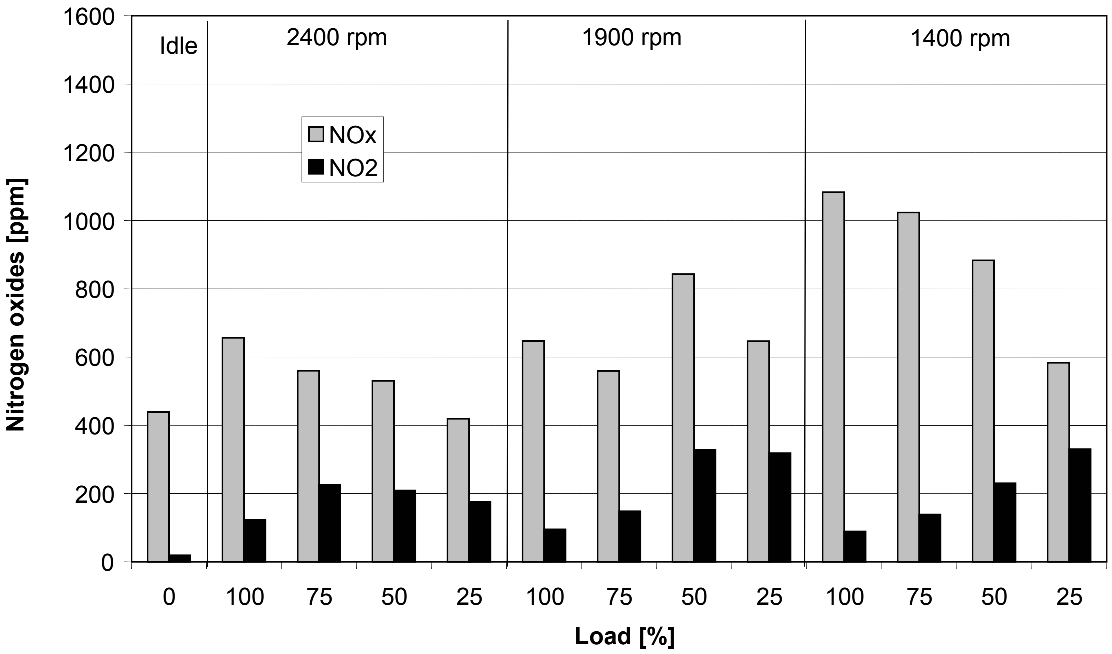


Fig. 2: Nitrogen oxide concentrations from vehicle No. 2 (SG 3309, 10 ppm S)

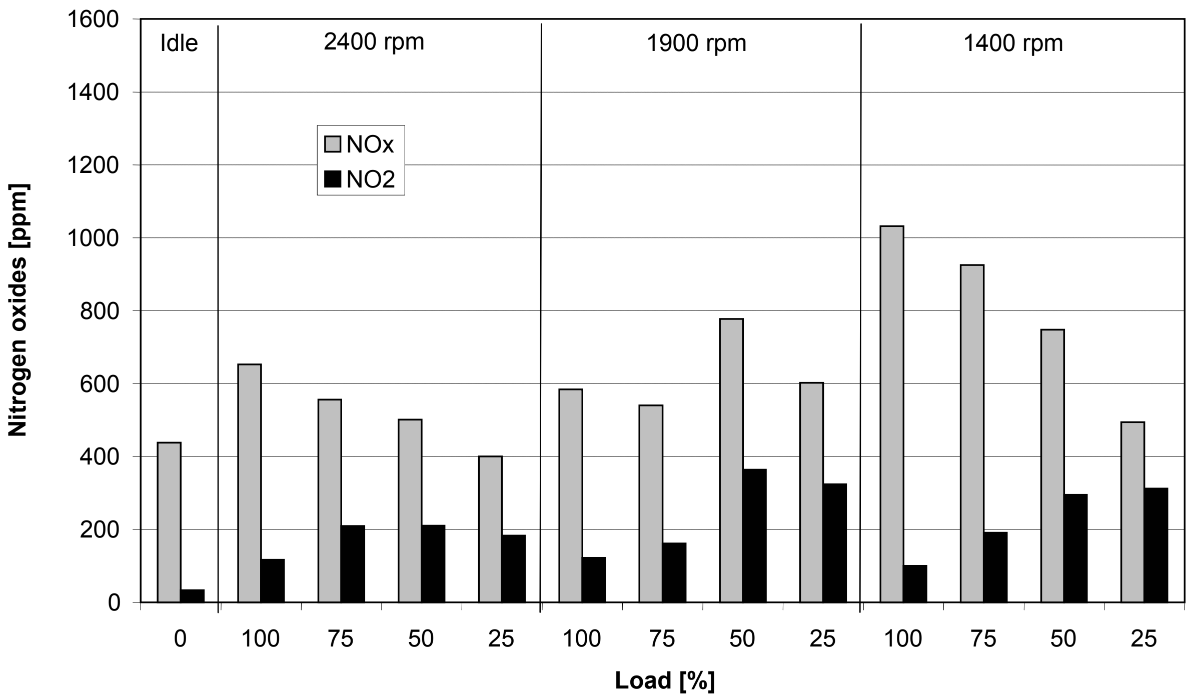


Fig. 3: Nitrogen oxide concentrations from vehicle No. 3 (ZH 540689)

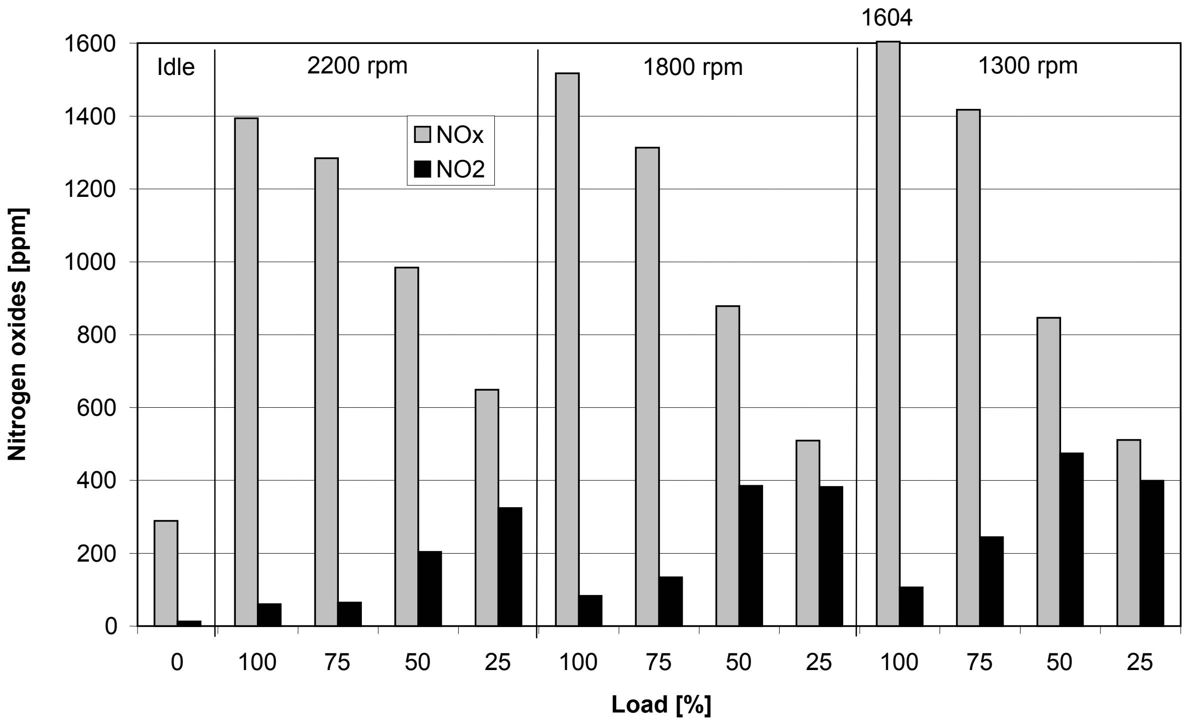


Fig. 4: Nitrogen oxide concentrations from vehicle No. 4 (SG 221820)

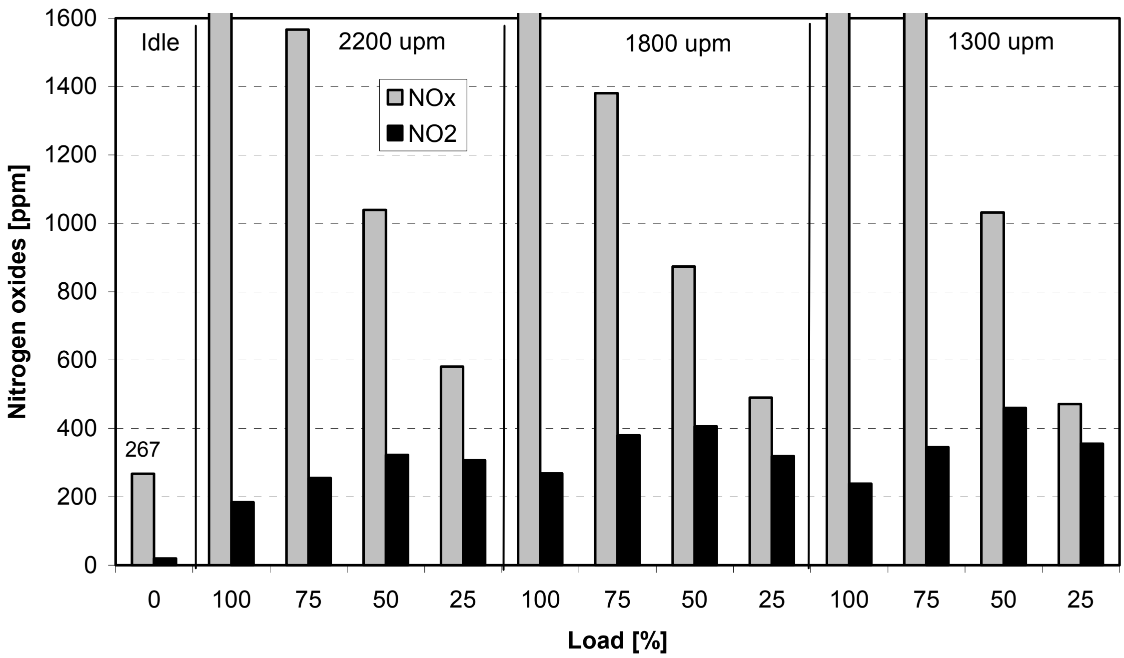


Fig. 5: Nitrogen dioxide fraction vs. load

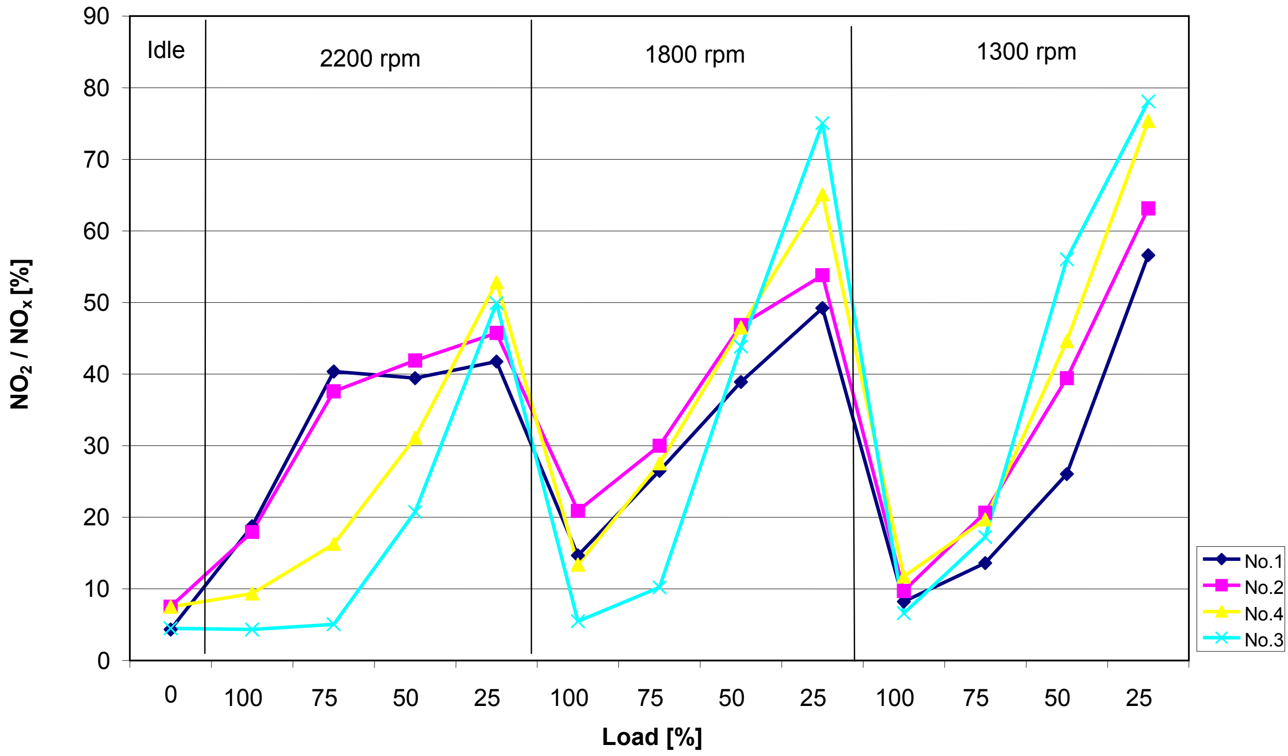


Fig. 6: Nitrogen dioxide concentration vs. load

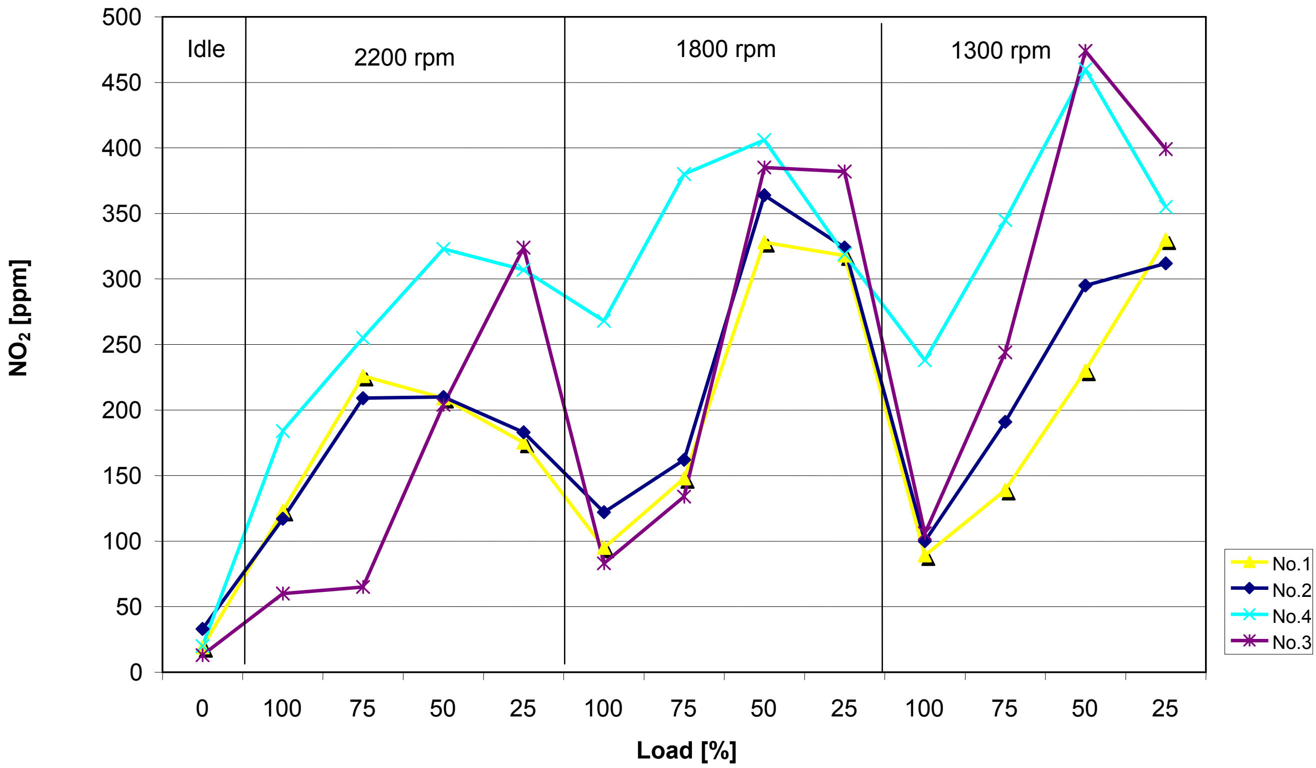


Fig. 7: Nitrogen dioxide fraction upstream and downstream of CRT system

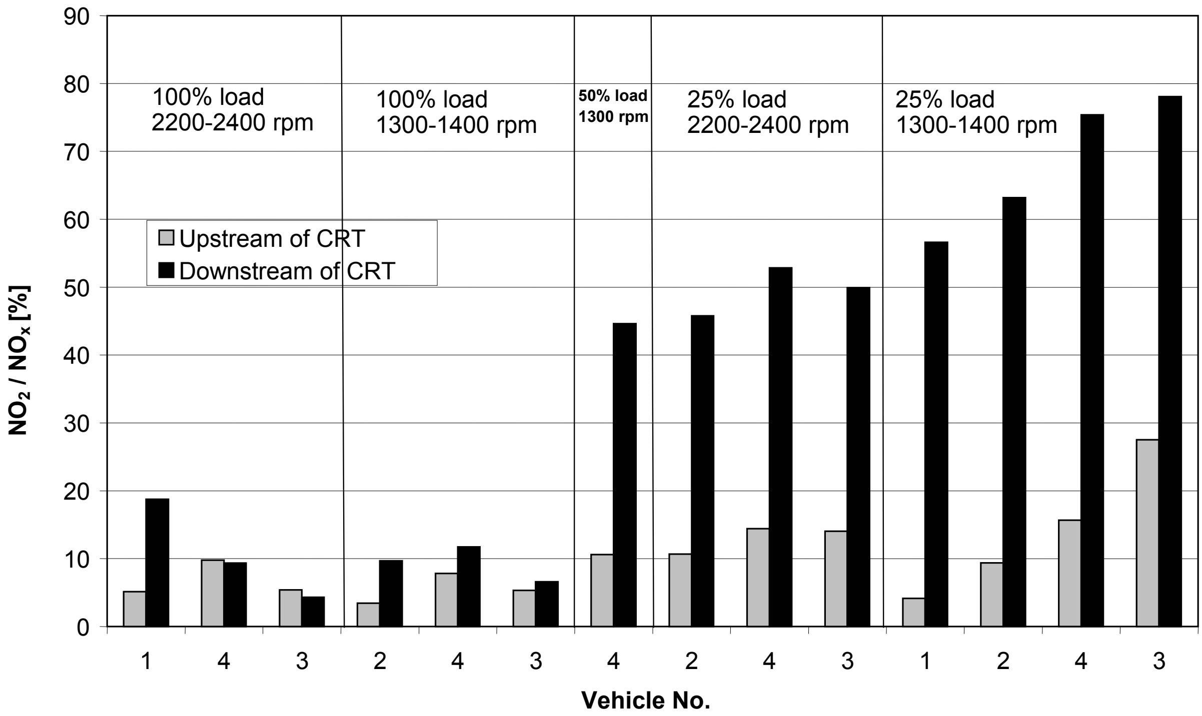


Fig. 8: Nitrogen dioxide concentrations upstream and downstream of CRT system

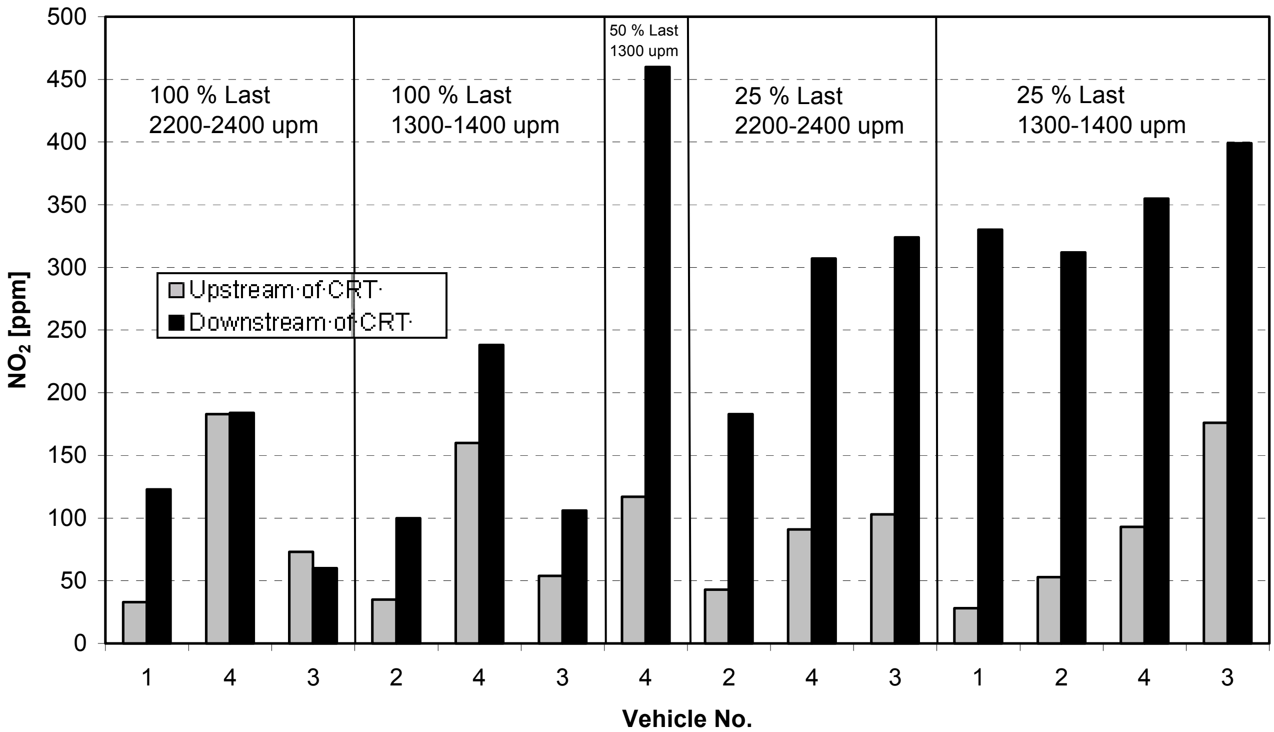
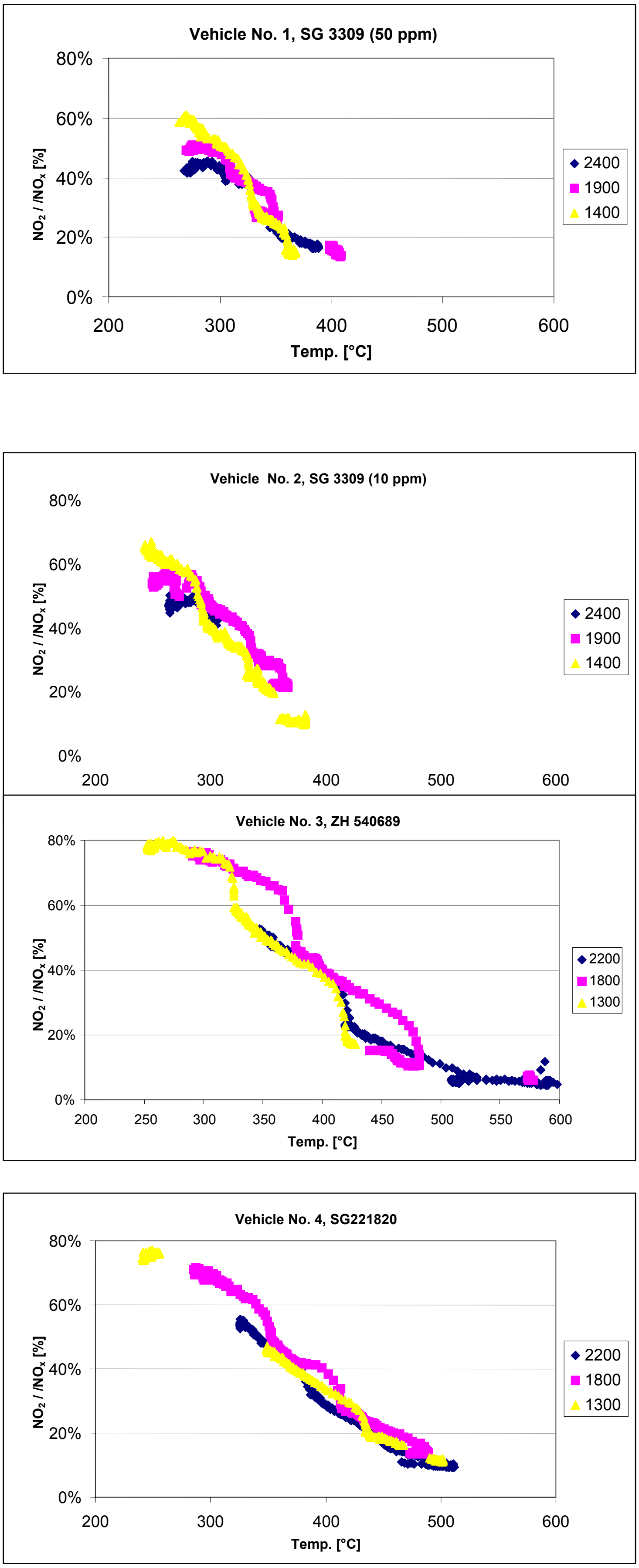


Fig. 9: *Formation of nitrogen dioxide (NO_2/NOx) as a function of exhaust gas temperature and speed*



Appendix 3: Information Note

Concerning the use of EMPA reports for advertising purposes as well as the publication of their contents

4 Under circumstances, EMPA test reports may be employed as an effective advertising means. However, in view of the independence and neutrality of the EMPA, it is required that certain rules be strictly adhered to. This lies in the interest of the client himself, since violations generally damage the image of the EMPA and thus decrease the effectiveness of the advertising. If a client issues a contract with the intention of utilizing the test report for advertising purposes, he is therefore advised to inform the respective EMPA department of this intention at the outset. In this way, he can also avoid unpleasant surprises (for example, the mentioning of fabrication secrets in the text of the report). The following rules must be adhered to:

5 1. Authorization Requirements

6 The use of EMPA test reports for advertising purposes as well as the publication of their contents in written or other form, including the mere mention of an EMPA test, is permitted only with the express written consent of the EMPA (Article 15, Paragraph 4 of the Government Regulation concerning the Swiss Federal Laboratories for Materials Testing and Research, January 13, 1993, SR 414.165). If the application is denied, the EMPA is not required to give grounds for the denial. As a rule, consents are given only for reports which are not more than two or three years old.

7 2. Completeness of the Submitted Text

8 Advertising text is to be submitted to the Marketing Staff at EMPA Dübendorf with its complete wording and with all illustrations. As a rule, this is accomplished through submission of the manuscripts and for printed texts, proof-sheets as well.

9 3. Reference to a Test Report

10 Every reference to an EMPA report must include the number and date of the EMPA report in question (for ex.: "see EMPA Test Report Nr. 423'511 from February 15, 2000").

11 4. Reference to the Tested Properties

12 Every reference to an EMPA test report for advertising purposes must mention expressly and completely the properties of the product which was tested (for ex.: "tested by the EMPA for heat conduction and flammability rating").

13 5. Completeness of Quotations

14 Excerpts from an EMPA test report must be given in their complete wording and must include accurate reproduction of any possible illustrations and explanations.

15 6. Truthfulness in Presentation

Comments, excerpts and conclusions may not be inserted into or added to the text in a misleading way. In particular, the reader may not be given the impression that:

- the EMPA has tested a representative number of objects, whereas in reality only one or a small number of objects were tested,
- the EMPA performs a running control of a product (whereas in reality, only a few samples were tested),
- further properties were tested (in reality, not tested), or

16 - advertising-oriented conclusions were formulated (in reality, formulated by the client).

17 7. Requirement of Openness

18 In referring to an EMPA test report, the client accepts the responsibility of providing the complete results of the respective report to every interested party in its full wording including all illustrations and possible explanations. At the same time, he releases the EMPA from its requirement of secrecy regarding these results, however not in regard to fabrication and business secrets (for ex. contents or methods of fabrication).

19 8. Time Limitation

20 The EMPA retains the right to set a time limit (as a rule, two years) on permits for advertising purposes or publications referred to in this information note. Here, likewise, the EMPA is not obliged to give grounds for setting the time limitation.

21 9. Fees

22 A fee will be set for the issuing of an advertising permit.

23 10. Consequences of Violations

In the case of violations of the regulations set forth in this information note, the EMPA retains the right to taking all further measures including a corrected presentation (provided to the interested parties who were incorrectly informed) as well as legal measures.

Dübendorf / St Gall / Thun, January 2001
Kn/Vs