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COMPARISON OF VENTILATION PRESCRIPTION CRITERIA FOR CERTIFICATION OF DIESEL ENGINE-EQUIPPED MINING MACHINERY

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MRL 89-101 (OP)
October 1989

Canada

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This report was presented
to the Technical Committee
of CSA Standard M424.2
at its meeting in Sudbury on
Wednesday, October 4, 1989.

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SUMMARY

This report presents results of a study of the toxic emissions of two substantially different types of diesel engine derived from CANMET contracted-out studies: the Deutz, 4-stroke, indirect injection type; and the Detroit Diesel Allison, 2-stroke, direct injection type.

The emissions are examined from the standpoints of: (1) ventilation requirements derived from certification testing, and (2) how the resultant ventilation levels are affected by the several toxicity criteria presently in use.

A recommendation is made to employ the CANMET Air Quality Index (AQI), a comprehensive toxicity criterion that rigourously accounts for a multitude of possible engine adjustments that dramatically affect the relationships among the several toxic constituents of diesel exhaust. It further gives credit where credit is due by permitting rational assessment of treatment technologies such as catalytic purifiers, ceramic filters and water scrubbers, and indicating the benefit of employing more expensive low sulphur fuel.

This recommendation applies to the certification processes. Ultimate possible application of the AQI to ambient compliance measurement on the part of operators and regulators, should await the development of light, inexpensive, multi-component analyzers. CANMET is undertaking the development of such equipment.

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INTRODUCTION

Prescribing the ventilation required for mining machinery as a result of exhaust emissions testing during the certification processes, has been a procedure in existence since diesel machines began to be used in underground mining in the late 1940s and early 50s.

Prior to 1978 in Canada, ventilation prescription was based on the worst operating load/speed condition from an emissions point of view, or on rules of thumb such as 100 cfm per bhp. This meant that at those operating conditions, the constituent producing the highest required exhaust gas dilution ratio (defined as the ratio of a constituent's undiluted concentration to its allowable ambient level), resulted in the maximum required fresh air for dilution to suitable ambient levels.

It was recognized however, that the several toxic constituents in diesel exhaust varied greatly for changes in injection timing, maximum fuel injection rate, rotational speed, etc. For example, when the engine systems were optimized to minimize NO generation, other constituents, such as unburned hydrocarbons, CO and soot would increase, sometimes dramatically, resulting in an apparent substantial increase in overall toxicity. However, soot until then, was not considered to have an impact on the health of workers, so that such constituent imbalances was not a matter of concern.

In 1978, as a result of a CANMET contracted-out study performed by I.W. French and Dr. Anne Mildon, a new comprehensive index of toxicity, involving the major gases of concern (carbon monoxide - CO, nitric oxide - NO, nitrogen dioxide - NO2, and sulphur dioxide - SO2) and particulate matter (soot), was formulated for a number of reasons including avoidance of anomalies produced by engine adjustments such as described above. This comprehensive criterion was called the Exhaust Quality Index (EQI), the form of which is as follows:

$$EQI = \frac{CO}{50} + \frac{NO}{25} + \frac{RCD}{2.0} + 1.5\left[\frac{SO2}{3} + \frac{RCD}{2.0}\right] + 1.2\left[\frac{NO2}{3} + \frac{RCD}{2.0}\right]$$

where all the gas concentrations have units of (ppm) and the Respirable Combustible Dust - RCD has units of (mg/m3 of dry exhaust gas). In engine testing the RCD and soot concentration are virtually synonomous.

Note that for the first time, by means of the above expression, the study directed attention of those concerned with the ventilation prescription process to the soot concentration. Indeed, when the various constituent concentrations in an exhaust stream are substituted into the equation, soot makes the biggest numerical contribution to the value of the Index, suggesting strongly that soot is the constituent of greatest health concern. It is only now that animal studies confirm this emphasis as being correct. The same study suggested that the maximum permissible value of the Index in the ambient air of a mine be placed at three (3), i.e.

$$AQImax = 3.0$$

When considering ambient mine air, the Index is called the Air Quality Index. The ratio of the EQI for undiluted exhaust to the maximum value of the AQI (3.0) in the ambient air, is the dilution ratio by which the engine exhaust flow must be multiplied to determine the amount of fresh air that must be supplied to maintain a suitable quality of ambient environment for the workers, i.e.

$$\text{dilution ratio} = \frac{EQI}{AQImax} = \frac{EQI}{3.0}$$

In 1988, EQI/AQI criterion was incorporated into the CSA national mining standard CSA M424.1-88 entitled "Flame-proof, non-rail-bound, diesel-powered machines for use in gassy underground coal mines." This coal mine standard having been completed, work was begun on CSA M424.2, the metal mine equivalent, entitled "Non-rail-bound, diesel-powered machines for use in non-gassy underground mines."

Because there are many more metal mine diesel machines than coal mine diesels, it was important that there be an understanding of the implications of using a new criterion for ventilation prescription. Studies of emissions in the past at CANMET/MRL/CEAL, indicate that the EQI criterion requires approximately 20% more ventilation than the worst constituent prescription (normally NO).

To confirm this conclusion for two substantially different diesel engines, and to compare the effects of employing the various ventilation criteria currently in use to the data for these engines, the following numerical study was undertaken and presented to the CSA Technical Committee during discussion of the ventilation prescription criterion clauses in the metal mine standard. This discussion led to the incorporation of the EQI criterion into the metal mine standard in September of 1988 by the Technical Committee. The standard is now in the ballotting process for adoption.

COMPARISON OF DEUTZ AND DDAD ENGINE EMISSIONS

Results of Engine Emissions Tests

During various past R/D programs, CANMET/MRL/CEAL, the Ontario Ministry Of Labour, and the United States Bureau of Mines, have issued contracts to ORTECH (formerly ORF), to undertake emissions evaluations of these two engines in order to compare the various points of interest. The the emissions results of three CANMET contracts are recorded in Table 1 below. Some input calculations for Table 1 are given in Appendix I.

Table 1 - Comparison of Deutz and DDAD*1 untreated engine emissions

item	units	Deutz (4-stroke) indirect injection F6L 714		DDAD (2-stroke) direct injection 8V71N		
load	%	100		100	75	50
speed	%	100		100	100	100
injectors		std		B5	B5	B5
injection		24	°BTDC	1.5 in	1.5 in	1.5 in
speed	rpm	2200	2200	2150	2150	2150
torque	lb.ft	300	318	540	405	270
power	bhp	126	133	221	166	110
air flow	lb/hr	1298	1320	3663	3776	3663
fuel flow	lb/hr	60.9	60.7	89.7	70.8	52.2
water	lb/hr	76.7	77.0	113.0	89.2	65.7
wet gas	lb/hr	1359	1381	3753	3847	3715
dry gas	lb/hr	1282	1304	3640	3758	3649
f/a ratio	-	0.0469	0.0460	0.0245	0.0188	0.0143
exh. temp.	deg F	1009	-	671	583	477
BSFC	lb/bhp.hr	0.480	0.456	0.406	0.427	0.475
CO2	%	10.3	10.0	5.2	4.0	3.0
CO	ppm	114	147	180	70	60
NO	ppm	510	552	1190	800	440
NO2	ppm	trace	trace	60	30	40
SO2 *3	ppm	-	87.2	46	-	-
soot	mg/m3	58.4	59.5	25.0*2	22.3	21.7
	g/kw.hr	0.30	0.30	0.21	0.18	0.27
	g/bhp.hr	0.22	0.22	0.16	0.13	0.20
EQI	-		183	145	-	-
ventiltn	cfm		17,700	39,100		
	cfm/bhp		133	177		
source	-	ORF	ORF		ORF	
		Mar 30/79	7-9097		-	
		#2722/02	#3503		#2512/5	

*1 DDAD - Detroit Diesel Allison Division

*2 extrapolated value

*3 0.2% sulphur in fuel

Comparison of Deutz and DDAD Emissions

The Deutz 4-stroke cycle series engines (912W, 714 and 413FW) are installed in approximately 67% of the underground diesel machinery in Canada. These engines are styled "indirect injection" (IDI) to indicate that there is a precombustion chamber developed carefully to minimize the toxic emissions so as to reduce the impact on health. While there are some variations among engines in these several series, their emissions are similar. They are also often derated which means that for underground service the maximum fuel injection rate is generally reduced to limit the maximum fuel air ratio to under 0.05. The consequence of these matters is that CO is maintained at very low values relative to those of a generation ago, and NO is likewise kept well below those values for current direct injection machines commonly employed for surface operation. These facts are confirmed by the data in Table 1. The comprehensive toxicity as measured by the EQI is 183 for this engine.

Direct injection (DI) engines do find a place underground but are less frequently encountered than IDI varieties. They typically have relatively high NO exhaust concentrations and high soot concentrations as they operate at higher fuel/air ratios. They are also more fuel efficient which is why they are preferred for surface applications. Except for the soot levels, the data in Table 1 substantiates these generalities for DDAD engine. The comprehensive toxicity of the emissions for this engine as measured by the EQI is 145. As the DDAD is a DI engine and operates on a 2-stroke cycle, it therefore represents one extreme while the Deutz varieties represent another, from an emissions point of view.

Comparison of Ventilation Requirements

The total air requirement for the DDAD engine is composed of combustion air and scavenge air. At or near the end of the power stroke, air is blown into the combustion chamber to assist in the removal of the combustion products from the cylinder and to provide air for the next combustion charge. This scavenge air dilutes the exhaust gas emissions concentrations by a factor which varies considerably, but can be 40% of the combustion air requirement.

This would suggest that the toxicity of the emissions for this engine as measured by the EQI would be low because of the scavenge air. This is in fact the case as indicated in Table 1. However, as shown in the ventilation equation below, this advantage is lost because the exhaust flow (Mdxg) has significantly increased, so that effect is cancelled because the two are multiplied together. The equation for dry ventilating air (Qdva) is:

$$Qdva = \frac{Mdxg \times \frac{EQI}{3.0} + \left[\frac{9H2\%}{100} - 1\right] Mf}{\text{dry gas density}}$$

where Mdxg is the flow of dry exhaust gas, H2 is the percent hydrogen in the fuel, and Mf is the fuel rate, all in consistent units.

When the data of Table 1, and the calculations of Appendix I, are employed, the ventilation quantities can be determined. To compare the two on a consistent basis it is necessary to compare the brake specific ventilation, i.e. the vent flow required per unit of power output.

When this is done, the advantage of the IDI engine becomes apparent, i.e. for the emissions of Table 1, the Deutz and DDAD brake specific ventilation rates are 133 and 177 cfm/bhp respectively. For these conditions, the DDAD engine requires 33% more ventilation per unit of power output to provide the same air quality, i.e an environment characterized by an AQI = 3.0.

It should be noted that the ventilation derived in this way is a maximum for the worst operating condition. The standards point out that this prescribed level could be reduced or altered by a number of site-determined factors, such as:

(1) altitude
(2) machine loading cycle
(3) relative efficiency of machine's exhaust dilution system
(4) multiple machine density
(5) mine layout
(6) efficiency of ventilation distribution,
(7) low sulphur fuel, etc.

This EQI criterion is proposed for ventilation prescription purposes in connection with the certification processes. The AQI is not presently recommended for compliance measurement purposes because suitable portable and economically priced equipment is not presently available to measure with reasonable effort, the five constituents that compose it. The development of such equipment for operators and regulators is in process.

COMPARISON OF VENTILATION-GOVERNING CRITERIA

Because there is present concern regarding which ventilation criterion to employ, Table 2 has been prepared to allow comparisons of ventilation computed according to several presently employed criteria. The soot has been assigned a limit of 1.0 as an interim measure to follow the example of MSHA/USA.

Table 2 - Comparison of ventilation criteria

engine	Deutz F6L 714				DDAD 8V71N		
	concen-tration	limit	dilution ratio	order	concen-tration	dilution ratio	order
EQI	183	3	61.0	1	145	48.3	1
soot	59.5	1.0	59.5	2	25.0	25.0	4
cfm/bhp =100	-	-	43.6	3	-	27.3	3
SO2*	87.2	2	43.6	4	46.0	23.0	5
NO	552	25	22.0	5	1190	47.6	2
CO	147	50	3.0	6	180	3.6	6

* 0.2% S in fuel assumed

It should be noted that both the EQI and governing constituent criterion - soot for the Deutz and NO for the DDAD - are virtually identical requirements. They however, require more ventilation than the 100 cfm/bhp rule of thumb (i.e. 38% for the Deutz and 74% for the DDAD), and considerably more ventilation than for the less important constituent CO.

Note also that the MSHA/USA NOx criterion limit of 12.5 ppm would require almost twice the ventilation for the DDAD than required by the EQI criterion.

If the TLV for SO2 were reduced to 1.0 ppm, as has been suggested, it would become the governing constituent. Alternatively, the fuel purchased would have to contain less sulphur than 0.2% by weight. It should be noted that if the percent sulphur in the fuel were 0.5% by weight, this constituent would govern the ventilation. The AQI approach is the only one which incorporates this variable along with the others, and by doing so gives credit for the extra expenditure associated with the purchase of low sulphur fuel.

Should the soot level ultimately be set lower than 1.0 mg/m3 (say that suggested by IW French - 0.5 mg/m3), then the dilution ratio for soot would double and soot would clearly govern. It therefore seems clear that a soot control strategy would be then be required as the ventilation requirement would be appreciably greater than present levels.

CONCLUSIONS

(1) There is an intrinsic advantage to the comprehensive toxicity index approach to ventilation prescription in order to account for multiple changes in emissions, to give new technology rigourous credit, and to credit the use of low sulphur fuel, etc.

(2) As most Deutz engines have emissions similar to the those quoted for the F6L 714, it seems safe to say that the IDI 4-stroke engines produce emissions significantly less toxic than those of the 2-stroke (when the EQI criterion is used to make the comparison). This can be seen easily when comparing the cfm/bhp values (133 to 177 cfm/bhp respectively).

(3) The EQI approach to emissions toxicity evaluation and ventilation calculation is unaffected by the 2-stroke dilution air. This is because dry gas flow increases with dilution and the AQI (and all toxic constituents on a volume basis) decreases in the same proportion with dilution. The product of the two in the ventilation equation makes the result independent of the scavenging flow.

APPENDIX I - INPUT CALCULATIONS FOR TABLE 1

<u>Auxilliary Deutz Calculations</u>

(1) water produced = 9 X 0.14 X 60.9 = 76.7 lb/hr

(2) soot unit conversion

$$58.4\ \frac{\text{mg}}{\text{m3}} \times \frac{1\ \text{m3}}{35.3\ \text{ft3}} \times \frac{\text{ft3}}{0.075\ \text{lb}} \times \frac{1282\ \text{lb}}{\text{hr}} \times \frac{1\ \text{g}}{1000\ \text{mg}} \times \frac{1}{126\ \text{hp}} \times \frac{\text{hp}}{0.746\ \text{kw}}$$

$$= 0.301\ \frac{\text{gr soot}}{\text{kw.hr}}$$

(3) CO Concentration

$$\text{CO} = \frac{84.5\ \text{gCO}}{\text{hr}} \times \frac{\text{kg}}{1000\ \text{g}} \times \frac{2.2\ \text{lb}}{\text{kg}} \times \frac{(1544/28) \times 528\ \text{ft3}}{2116\ \ \text{lbCO}}$$

$$\times \frac{\text{hr}}{1304\ \text{lbdg}} \times \frac{0.075\ \text{lb dg}}{\text{ft3 dg}} \times 10^{6} = 147\ \text{ppm}$$

(4) NO Concentration $= \dfrac{340 \times 2.2 \times 0.075}{0.0779 \times 1304} \times 10^{3} = 552\ \text{ppm}$

(5) Soot Concentration

$$\frac{29.3\ \text{g soot}}{\text{hr}} \times \frac{1000\ \text{mg}}{\text{g}} \times \frac{\text{hr}}{1304\ \text{lbdg}} \times \frac{0.075\ \text{lbdg}}{\text{ft3 dg}} \times \frac{35.3\ \text{ft3}}{\text{m3}} = 59.5\ \text{mg/m3}$$

Auxilliary DDAD Calculations

(1) $\text{air flow} = \frac{814 \text{ dry std ft3}}{\text{min}} \times \frac{0.075 \text{ lb}}{\text{ft3}} \times \frac{60 \text{ min}}{\text{hr}} = 3{,}663 \text{ lb/hr}$

(2) $25.0 \times \frac{1}{35.3} \times \frac{1}{0.075} \times 3640 \times \frac{1}{1000 \times 221 \times 0.746} = 0.208 \frac{\text{gr soot}}{\text{kw.hr}}$

Comparative Prescribed Ventilation Calculations

$$SO2_{\text{Deutz}} = \frac{60.7 \text{ lb}}{\text{hr}} \times \frac{0.002 \text{ lbS}}{\text{lb fuel}} \times \frac{64 \text{ lbSO2}}{32 \text{ lbS}} \times \frac{\text{hr}}{1304 \text{ lbdg}} \times \frac{30 \text{ lbdg}}{64 \text{ lbSO2}} \times 10^6$$

$= 87.2$ ppm

$$EQI_{\text{Deutz}} = \frac{147}{50} + \frac{552}{25} + \frac{59.5}{2.0} + 1.5 \left\{\frac{87}{3} + \frac{59.5}{2.0}\right\} + 1.2 \left(\frac{10}{3} + \frac{59.5}{2.0}\right\}$$

$= 2.9 + 22.1 + 29.8 + 88.2 + 39.7 = 182.7$

$$SO2_{\text{DDAD}} = 89.7 \times 0.002 \times 2 \times (1/3640) \times 30/64 \times 10^6 = 46.1 \text{ ppm}$$

$$EQI_{\text{DDAD}} = \frac{180}{50} + \frac{1190}{25} + \frac{25.0}{2.0} + 1.5 \left\{\frac{46.1}{3} + \frac{25.0}{2.0}\right\} + 1.2 \left\{\frac{60}{3} + \frac{25.0}{2.0}\right\}$$

$= 3.6 + 47.6 + 12.5 + 41.8 + 39.0 = 144.5$

$$\text{Ventilation Deutz} = \frac{1304 \times 183/3 + (9 \times 0.14 - 1) \times 60.7}{3600 \times 0.075}$$

$$= \frac{79{,}544 + 16}{270} = 295 \text{ cfs} = 17{,}700 \text{ cfm}$$

$= 133$ cfm/bhp

$$\text{Ventilation DDAD} = \frac{3640 \times 145/3 + (9 \times 0.14 - 1) \times 89.7}{3600 \times 0.075}$$

$$= \frac{175{,}933 + 23}{270} = 652 \text{ cfs} = 39{,}100 \text{ cfm}$$

$= 177$ cfm/bhp

DDAD dilution ratio (100 cfm/bhp rule)

$$= \frac{\text{ventilation flow}}{\text{exhaust flow}} = \frac{100 \times 221}{3640/(60 \times 0.075)}$$

$$\doteq 27.3$$

Deutz dilution ratio (100 cfm/bhp rule)

$$= \frac{100 \times 126}{1304/(60 \times 0.075)} = 43.6$$

CSA/17/89/01