Do electrostatic precipitators remove fine particles?

Summary.

Claims that electrostatic precipitators are incapable of removing 'fine' or 'ultra fine' particles, such as those found in vehicle emissions, are based on the results of unreliable or inappropriate testing or on a misunderstanding of the practicalities of testing under field conditions. An examination of a range of test results shows that electrostatic precipitators designed for the removal of vehicle exhaust particles and operating according to manufacturers specifications relating to air speed, can be expected to remove particles less than 1 micron in diameter with an efficiency in excess of 90% and that there is no significant drop in efficiency over this range.

Electrostatic precipitators are a safe and effective method of removing particle emissions from vehicles in enclosed spaces and, properly operated and maintained, are capable of removing a high proportion of all sizes of particles found in vehicle emissions. Thus they provide effective protection from the adverse health effects of these particles.

Introduction.

In the continuing controversy over the possibility of using electrostatic precipitators to filter the air in, and emitted from, road tunnels, local Roads Authorities have frequently claimed that such precipitators lack the ability to effectively remove 'fine' particles.

As it is these fine particles (mainly less than 1 micrometre in diameter) which are most implicated in adverse impacts on health, the conclusion is drawn that although the precipitators are effective in removing larger, more visible, particles, they do not provide a proportionate reduction in those particles which are of most concern from a public health perspective.

This had led electrostatic precipitation to be characterised as a 'high tech placebo', not worthy of consideration as a technique for use in road tunnels.

This document aims to examine the basis of such claims.

Fine Particles

There is considerable confusion about the use of the terms 'fine' and 'ultra fine' in describing particle size. During the course of this debate the terms have often been used incorrectly and sometimes misleadingly. For clarity, particles are best referred to by their aerodynamic diameter.

PARTICLE size	10 µm	2.5 µm	1.0 µm	0.1 mm	0.01 µm
Compare with	grapefruit	golf ball	cherry	wheat seed	sand grain
Number for equal mass	1	64	1000	1000,000	1,000,000,000
Surface area for equal mass	1	4	10	100	1000
Functional classification (after Morawska)	Coarse mode		Accumulation mode		Nuclei mode

Table 1. Classification of particles by size and function.

While the US EPA refers to particles larger than 2.5 µm (PM2.5) as coarse particles and those smaller as fine, the more general usage is to regard particles between 10 µm (PM10) and 1 µm (PM1) as being 'coarse' and below 1 µm as being 'fine'. This division coincides generally with the natural division between particles formed by combustion processes and those formed by mechanical processes.[1] The terms 'ultra fine' and 'nano particle' are also used for those particles whose diameter is best described in nanometres, perhaps less than PM 0.3 (300 nm). The significance of this division is that particles in this size range behave in a different manner to those with a larger diameter, tending to 'accumulate' into larger particles with time and proximity.

It is particles of 1 micron diameter and less which are of greatest importance in the production of adverse health impacts.[2] They are also the most difficult to measure.

Electrostatic precipitators

The operation of electrostatic precipitators depends on the ability of electrically charged surfaces to attract small objects, the phenomenon which lead to the first discovery of electricity.

There are a number of different types of filtration systems where either the collecting filter or the particles themselves receive an electric charge but in the electrostatic precipitator, both the particles and the collecting plates are charged. There are also a number of distinct types and designs of precipitator falling into two broad groups, those which operate relatively high temperatures and with relatively high concentrations of dust (as found in industrial applications such as steel mills and cement kilns) and those which operate at low temperatures and relatively low concentrations of dust. Equipment used in air conditioning, control of tobacco, paper and other dust, and in road tunnels fall into the second group.

The operational characteristics of the two general types differ widely and conclusions drawn from experience with one type rarely apply to the other.

Precipitators have been used in industrial and defence applications for many years but their use with vehicle emissions in tunnels is relatively recent, having first been used in the late 1970s. An important impetus for the development of 'low temperature' precipitators was the requirement to remove suspended oil particles from the atmosphere inside nuclear submarines and it was for this application that the testing method using DOS aerosol, referred to later, was developed.

Current use of Electrostatic Precipitator equipment in road tunnels

According to information provided by Matsushita Electrical Co of Japan, the first use of electrostatic precipitator equipment in road tunnels was in 1979 in the Taruga tunnel in Japan. This tunnel used 10 EP units with a total cleaning capacity of 240 m^3/sec. This was followed in 1982 by the installation of 2 units with a total capacity of 60m^3/sec in the Suginami-ku tunnel.

Matsushita report that during the period from 1980 -1989, they installed EP's with a total air cleaning capacity of 3280 m^3/sec in 7 different tunnels and between 1990 -1998 a total of 6970 m^3/sec of cleaning capacity in a total of 14 tunnels.

Equipment from other manufacturers has been installed in several other tunnels in Japan.[3] and 41 out of the 60 or so 'long' tunnels in Japan (over 2 km) are filtered.

One of the more spectacular installations is that in the trans Tokyo Bay Aqua-line, with a total cleaning capacity of over 1300 m^3/sec. Because of low usage of the tunnel due to the high tolls applied, reported in the October 2002 issue of the National Geographic Magazine to be as high as $US 50 per round trip, the actual operation of this equipment has been delayed.

In Norway, up until 2000, electrostatic precipitators with a total cleaning capacity of approximately 1400 cubic meters per second had been installed in 5 tunnels, however, due to lower than expected pollution volumes (and other factors) some of these are not operating now. Much of this equipment was installed for the protection of the external atmosphere because of the common Norwegian practice of using longitudinal ventilation with portal emissions, giving rise to the possibility of excessive ground level concentrations of particle emissions. The Nygard tunnel in Bergen is such a tunnel.

Since 2000 the Leardal tunnel, the worlds longest, with a cleaning capacity of 180 m^3/sec for both particles and nitrogen dioxide and the Stromsas tunnel with a cleaning capacity of 650 m^3/sec (4 units for particles only) have been opened and are operating. These tunnels use 'in tunnel' cleaning techniques and, more importantly, are designed specifically to make full use of the engineering advantages of filtration. The tunnel ventilation systems cannot maintain acceptable in-tunnel conditions under full load without the use of filtration. The Bragernes tunnel, using stack fitted filtration (250 m^3/sec), opened recently.

All Norwegian filtration equipment, with the exception of that used in the Oslo, Grandfos and Bragernes tunnels, was built by CTA International ASA. The Bragernes filtration equipment was built by Xtor Inc.

In Korea, one filtered tunnel is operating (Chinbu) with CTA provided equipment, and between 6 and 8 others planned in the near future, for which Matsushita, CTA and several other companies are in competition for the supply of filtration equipment.[4]

Removal of fine particles by Electrostatic Filters

The first introduction which many tunnel and ventilation engineers had to the potential for the use of electrostatic precipitators in tunnels was a report by Jan Eric Henning and Kjell Ottar Berge at the XX World Tunnel Congress in Montreal in September 1995. [5]

This report described the progress being made in Norway with the installation of electrostatic precipitator filtration equipment and future plans, including those for the highly advanced Laerdal tunnel, which, on completion, would become the worlds longest tunnel by a considerable margin. The design of this tunnel depended on the effective operation of both particle and NO_2 cleaning systems.

As part of their presentation they used a graph, reproduced here, saying it showed the 'typical' removal efficiency of various particle size classes of an unidentified electrostatic precipitator.

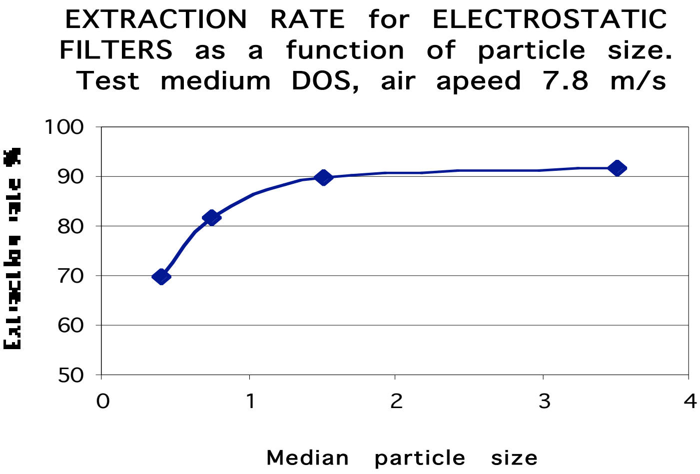

Fig. 1. Extraction rate of electrostatic precipitator using DOS as a test aerosol. (The air speed of 7.8 m/s indicates the precipitator was being operated above its design speed of about 4 m/s.) (data replotted)

Henning and Berge make no comment about the apparently low efficiency in the removal of the finest particles perhaps because they, in Norway, were more concerned about the larger dust particles of mechanical origin resulting from the use of studded tyres. It could also be that, at that time, the evidence about the health problems relating specifically to particles of less than 1 micron was not so extensive as it is now.

Two crucial, but ignored, factors in this report were the unusually high air speed in the precipitator, about double that usually used at that time, and the use of DOS (Dioctyl Sebacete), as a test medium rather than (say) diesel exhaust. DOS is an oily liquid which, when atomised, produces a fine aerosol containing particles, mainly less than 5 microns in diameter. Tests based on the use of this substance were first developed to test the removal efficiency of oil mists by electrostatic precipitators.

The questions raised by this data obviously required investigation as it was known that diesel exhaust at least was largely made up of particles of less than 1 micron in diameter[6]. Furthermore, the data did not seem to agree with on-site observation, which showed a higher efficiency, nor with the acceptance testing for the first set of Norwegian precipitators. In these tests, using tunnel emissions, efficiency of removal of the finest size class measured (0.3-0.5µ) was between 85 and 90%.

CTA International arranged for a series of comparison tests of removal efficiencies using DOS or diesel exhaust under otherwise identical conditions, to be carried out by an independent testing unit at the Department of Mechanical Engineering. HiST – Trondheim, Norway.[7] The comparison tests were carried out in conjunction with other developmental tests of methods for increasing the air flow through filters.

The test series measured the efficiency of removal of DOS and Diesel particulate under various air flows and different ioniser and collector voltages.

Particle removal was determined by counting the number of particles upstream and downstream of the test-filter using a Met One 200L optical particle counter. Counts are distributed into six ranges (0.3 - 0.5µm, 0.5 - 1.0 µm, 1.0 - 2.0 µm, 2.0 -5.0 µm, 5.0 - 10 µm and >10 µm). Particle counting is done successively upstream and downstream of the filter for one-minute periods. The counting cycle is repeated six times per test. Between each count, the particle counter is flushed out for one minute. The fractional efficiency is calculated according to the EUROVENT 4/9 standard.

Results

The essential results are summarised in the following three figures.

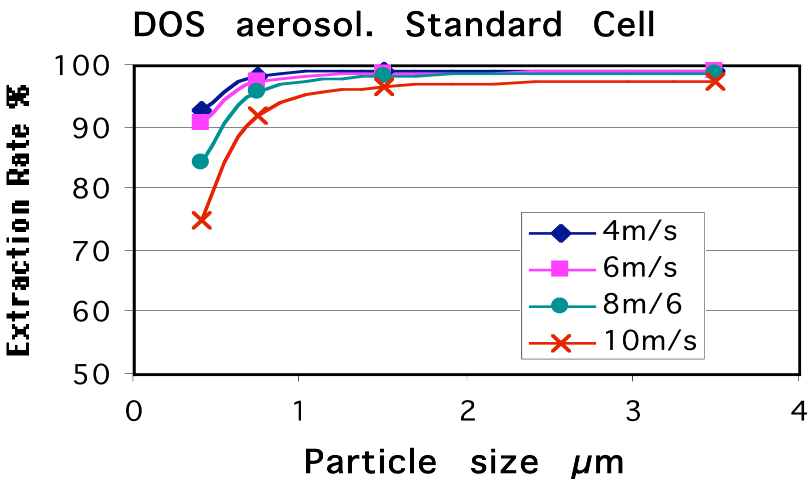

Fig 2. Standard CTA EP cell operated at design air speed (4-6 m/s) and at excessive speed (8-10 m/s). DOS aerosol. (data replotted)

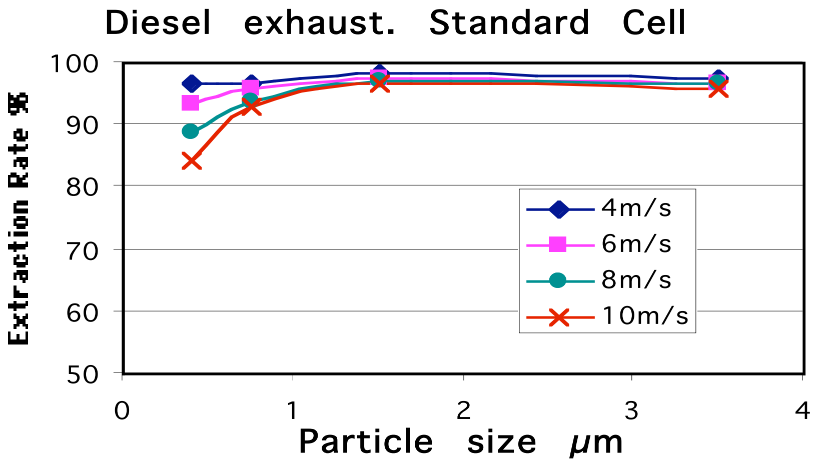

Fig3. Standard CTA EP cell operated at design air speed (4-6 m/s) and at excessive speed (8-10 m/s). Diesel aerosol. (data replotted)

The standard cells designed for operation at 4.5 m/s give removal efficiencies for particle size class 0.3-0.5µ of above 90% with DOS aerosol and above 93% with diesel exhaust when operated close to design speed, however this efficiency drops markedly when the cells are operated at air speeds above their design optimum.

The observed difference in removal efficiency for DOS and diesel aerosol was suggested by the testing agency to be due to the difference in electrical conductivity of the two substances, DOS being non conductive and diesel exhaust, containing carbon particles, being electrically conductive.

The crucial point is that the DOS test medium underestimates the capacity of the precipitator to remove diesel exhaust and thus is not a reliable indicator of performance for this task. The degree of underestimation increases as the precipitator is increasingly stressed by increasing air speed.

Diesel exhaust is clearly a more appropriate test medium than DOS to assess precipitator performance with vehicle exhaust.

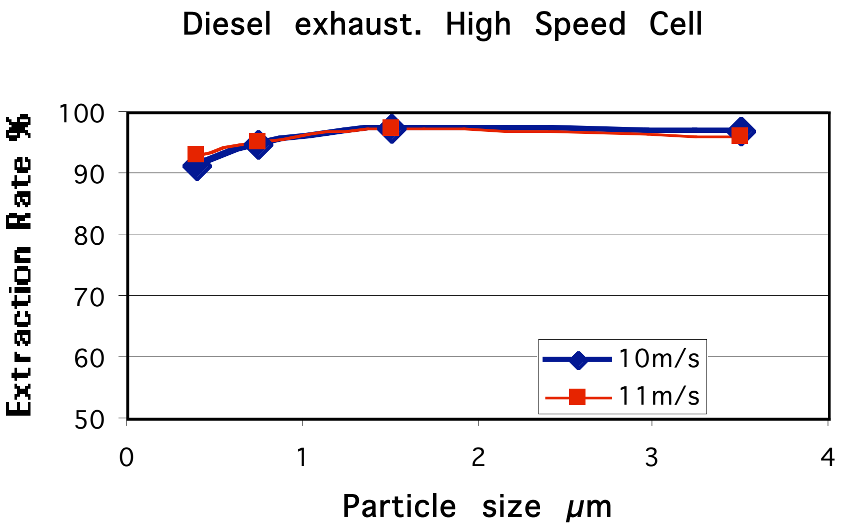

Fig 4.CTA High speed cell optimised for use higher air speeds. -diesel aerosol. (data replotted)

The 'High speed' cells (which are deeper and operate at higher ionizer voltages) show high efficiency of removal for all size classes of diesel exhaust at air speeds of 10 and 11 m/s.

These results show that the CTA precipitator cells perform better than the unidentified cells used in the test reported by Henning and Berge. They also provide a clear explanation of the apparent low removal efficiency of the finest particle size ranges, which is shown to be due to the use of an inappropriate measuring technique. To this must be added the probability that the results reported were of a precipitator operation outside its optimum operating range.

Performance of installed equipment.

Some reports question the performance of equipment under operational situations, however it is difficult to determine upon what objective measurements these reports are based. Part of the explanation may be that the reported efficiencies achieved during compliance testing are often somewhat lower than those achieved under optimal laboratory conditions.

It is important to clearly distinguish between what may be expected of laboratory conditions and of compliance testing which is, of course, carried out in situ in an operating tunnel.

In practice, efficiency testing involves the sequential measurement of air quality upstream and down stream of the filter. Ideally the traffic flow should be constant, with a constant levels of particles. This is rarely achievable.

Efficiency results are reported as a percentage of the difference between up stream and downstream particle levels. Ultimately the efficiency determined will depend on the degree of cleanliness achieved in the tunnel on the downstream side of the filter, however the air passing through the filter may not be the only source of particles at the measuring location. All of the data for installed equipment in Norway is for by - pass systems of one type on another so not only is there the possibility of re-entrained dust from road and wall surfaces but in the case of ceiling mounted systems there is the possibility of turbulent mixing of the uncleaned portion of the air flow.

Simple mathematics would suggest that the lowest particle level at which a realistic test could carried out would be round 500µg/m^3, as this would imply a downstream particle level of 25µg/m^3 to demonstrate an efficiency of 95% If the particle level in the down stream air flow cannot be reduced below about 20 µg/m^3 in the absence of traffic, no realistic test could be carried out unless the up stream particle concentration is well above 500 µg/m^3 and it is often difficult to achieve this level of aerosol in a tunnel which has just started operating.

During the compliance testing for the Laerdal tunnel, winter traffic was so low that it was found necessary to introduce several diesel compressors into the tunnel and to operate street sweeping equipment to raise sufficient dust for a realistic test to be carried out.[8] In spite of these difficulties adequate removal efficiencies were demonstrated.

Considering this, it is possible to understand the apparent failure of the Nygard tunnel (reported in the Bongiorno Report) to achieve 'acceptable' efficiencies of removal. These test results, suggested that particle removal efficiency of precipitators in this tunnel was low (0.3-0.5μ, 59%; 0.5-1.0μ, 71%; 1-2μ, 84%; 2-5μ 88%), but it was noted that, after adjustment "an average of 80 to 83% has been achieved."

This tunnel in central Bergen has a ceiling mounted precipitator, on what are effectively a shelf, above the traffic stream. It is longitudinally ventilated with portal emissions at ground level in a built up area. The in-tunnel particle load has apparently never exceeded 300 μg'm^3. To be able to report a 90% efficiency of removal, the particle level down stream of the filter would have to be less than 30μg/m^3 and this concentration would have to be achieved in the presence of moving traffic, which would provide a significant additional input of particles.

By concentrating on results expressed as a percentage, the actual conditions produced are ignored. If the 'in-tunnel' particle levels were about 200 μg/m^3, as would appear likely, the report of an overall particle removal efficiency of between 75 and 80% implies that the actual particle concentration downstream of the precipitators was less than 50 μg/m^3, a truly remarkable achievement measured above a busy traffic way. Rather than showing a failure of the filter equipment, the results actually show a success and they were regarded as such by the responsible Norwegian authorities.

The Bongiorno report rather disingenuously comments that the Norwegian Public Roads Administration engineers in Bergen were 'unenthusiastic' about electrostatic precipitators, regarding the Nygard installation as a 'waste of money'. It is clear that the cleaning equipment was required by the civil authorities, not for in-tunnel conditions (the responsibility of the roads authority), but to protect their city and its residents from the possible impacts of exhaust emissions from the portals.

During winter, Bergen experiences significant particle pollution, due in part to the use of wood fires for heating. Following considerable recent local public protest about the extra impact of tunnel emissions and the failure to use the equipment installed (at a cost of 15 million NoK), the settings on the Nygard equipment have now been adjusted to switch the filters on when in-tunnel particle concentrations reach 200 μg/m^3, rather than the previous 300 μg/m^3.[9] In addition, from 2005, the filters in the tunnel will be activated when external particle levels exceed 50μg/m^3.

It is clear that the conclusion in the Bongiorno report, relating to the Nygard tunnel, is not justified.

The test results for both the Stromsas and Chinbu tunnels give no evidence that the efficiency of installed filtration systems is likely to be significantly less than 90% for all particle size classes

Stromsas Tunnel. Contract Requirement			Achieved - as measured 05-11-2001	
Particle size	Removal Efficiency %		Particle size	Removal Efficiency %
	Summer	Winter		
0.01 - 1.0 μm	87	88	0.3 - 1.0 μm	92.6
2.0 - 5.0 μm	89	92	1.0 - 5.0 μm	93.6
5.0 -10.0 μm	90	92	5.0 - 10.0 μm	89.9

Table 2. Result of Stromsas tunnel Efficiency test[10] This test result was accepted as fulfilling both the summer and winter requirement because of the technical difficulties experienced with providing sufficient particle 'loading' for a realistic test.

Remaining questions

The test data available from these tests leave open the question of the efficiency of removal of particles less than 0.3 microns. Largely for practical reasons, these have not been measured as part of the contract compliance testing for electrostatic precipitators, as the measurement of these smaller particles requires different instrumentation. However evidence is available from other sources.

In her evidence to the third inquiry into the M5 ventilation stack by the General Purpose Standing Committee No5 of the NSW Legislative Council,(Sub.No.95), Prof Lidia Morawska stated "Thus, in summary in relation to the M5 stack operation,......it can be expected that electrostatic precipitation would be a very efficient method of removal of all particles, and specifically the very small particles emitted by motor vehicles, provided that the precipitator operates within the optimal range of its operating conditions."

In support of this contention and as part of her evidence she presented a graph relating the efficiency of removal of tobacco smoke aerosol under optimal and non optimal conditions. The data had been published in the journal *Indoor Air.*[11]

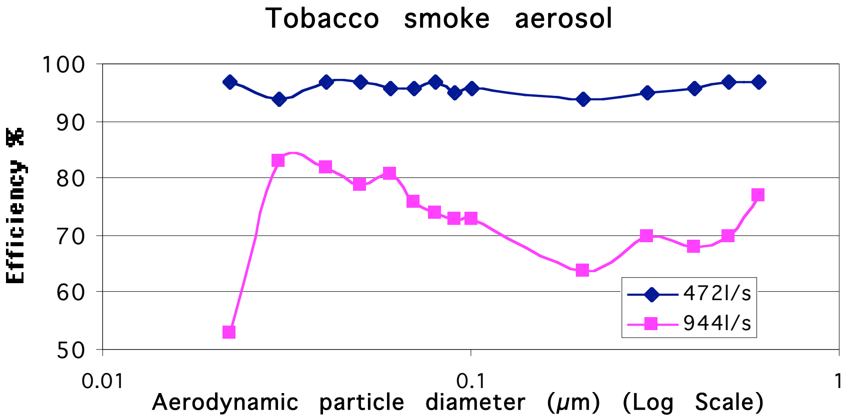

Fig 5. Particle removal efficiency achieved by an Email IONITRON electrostatic precipitator operating at the manufacturer's specified air flow and at double this flow. The results show removal efficiency well in excess of 90% for 'ultrafine' particles ranging in size between 0.6 and 0.022 microns, but this performance is severely degraded at increased air flow rates. (Data reconstructed and replotted)

The size range of this study corresponds closely with size distribution of vehicle emissions and overlaps the range covered by compliance testing of CTA precipitators. These results show a similar efficiency and do not demonstrate any drop in efficiency as particles become smaller.

Conclusion

Taken together, these data confirm that appropriately operated electrostatic precipitator equipment can achieve a removal efficiency in excess of 90% for all size classes of particles likely to be found in road tunnels. When operated under appropriate conditions the electrostatic precipitators installed recently by CTA International can achieve efficiencies above 90% for all size classes. This applies both in laboratory tests under standardised conditions and in field situations. It is to be expected that other manufacturers are likely to be able to either match this efficiency or to provide equipment which has other compensating advantages.

At least some reports which appear to show results to the contrary are based either on inappropriate testing procedures or on a lack of understanding of the practicalities of field testing. Some interpretations which have been applied to available results stem from a simple misunderstanding of the processes involved and ignore the caveats placed on the test results by the testing agencies.

Unless reliable evidence to the contrary appears, the ability of electrostatic precipitators to remove all classes of particles must be regarded as established because there is now no justification for a claim that appropriately designed electrostatic precipitators are incapable of removing the finest atmospheric particles from vehicle emissions at high rates of efficiency.

Electrostatic precipitators are a safe and effective method of removing particle emissions from vehicles in enclosed spaces and, properly operated and maintained, are capable of removing a high proportion of all sizes of particles found in vehicle emissions. Thus they provide effective protection from the adverse health effects of these particles.

Mark Curran

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