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DUST SAMPLING CRITERIA

(A contribution to standardisation of
"total dust" measurements)

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DUST SAMPLING CRITERIA*

(A contribution to standardisation of "total dust" measurements)

To measure the gravimetric "total dust" concentration in the indoor industrial environment on behalf of occupational hygiene a simple criterion is needed which enables the choice of the correct sampling device for each type of dust on the working place. Often it is more important to obtain comparable results with different instruments in different environments, than to have representative samples. This is because in industry the weight of the sample may be determined by the fraction of coarse dust, and strongly depends on the cut-off particle diameter of the inlet of the sampling instrument.

To be able to compare samples of "total dust", two requirements should be satisfied:

1. All samplers should have the same "cut-off particle radius", where the sampling efficiency sharply decreases to zero.
2. The aspirating efficiency should be insensitive to wind velocities and different geometries of the inlet.

To obtain comparable results several institutions in Europe have agreed to measure the "total dust" concentration with a horizontal suction velocity of about 1.25 m/s in the entry of the sampler. Usually there is an absolute filter near the entrance of the sampler. Here I want to show how these agreements can be refined, to obtain results of dust measurements, which are better comparable and less sensitive to local disturbances in the industrial environment. For determination of the inhalable fraction (Ogden, Birkett, 1977) the particle size distribution should be measured with the same inlet.

CURRENT SAMPLING CRITERIA

At present there are two well known sampling criteria.

A. Levin (1957) finds from basic equations of motion of the particles that due to their inertia big particles are sampled with a reduced efficiency:

$$E_{lev} = 1 - 0.8\,k + 0.08\,k^2 \tag{1}$$

where $k = \sqrt{\dfrac{4\pi\tau^2 v_s{}^3}{Q}} = \text{const.}\ d_p{}^5 Q^{-0.5}$ (Levin number) (2)

τ = relaxation time (s)

d_p = particle diameter (m)

For an efficiency of $E_{lev} > 96$ % the Levin number becomes: $k < 0.05$.

This is a fundamental dynamic limitation which works only if there is no influence of the finite size of the sampling orifice.

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B. Davies (1968) gives a criterion for representative sampling, which is limited by the influence of gravity on one hand and by the influence of inertia on the other:

1. due to gravity the efficiency is in error less than $\pm$ 4%, if the suction velocity, u_o, is higher than 25 times the settling velocity, v_s:

$$u_o > 25\, v_s \tag{3}$$

2. due to inertia the efficiency is reduced less than 1.6%, if the radius of the sampling tube, R_o, is more than five times the critial stop distance of the particle, d_s:

$$R_o > 5\, d_s \tag{4}$$

where d_s is the critical stopdistance as it was defined by Davies (1968):

$$d_s = \left(\frac{Q\tau}{4\pi}\right)^{1/3} \tag{5}$$

For a tube, the suction velocity u_o can be expressed in terms of the tube radius R_o, by $u_o = Q / (\pi R_o^2)$ so that both assumptions limit the range of acceptable radii. This range is given by:

$$5\, d_s < R_o < 0.4\, l_o \qquad \text{where } l_o = \sqrt{\frac{Q}{4\pi v_s}} \tag{6), (7}$$

For particles in the flow field of a point sink, l_o is the distance between the sink and the point below the sink where the vertical velocity of the air equals the sedimentation velocity of the particle. Therefore the influence of gravity is characterized by the distance l_o, or by the dimensionless gravity-parameter $m_g = \frac{R_o}{l_o}$. (8)

In the same way the influence of inertia is characterized by the critical stop distance d_s, or by the dimensionless inertia parameter

$$m_i = \frac{R_o}{d_s} \tag{9}$$

The Graphical Presentation

Written in the commonly used dimensionless magnitudes (Stk_o, $\frac{v_s}{u_o}$) with $Stk_o = \frac{\tau u_o}{D_o}$ the criterion (3), (4) gives (figure 1) :

1. gravity limit $\frac{v_s}{u_o} < 0.04$ for an efficiency $96\% < E < 104\%$ (10)

2. inertia limit $Stk_o < 0.016$ for an efficiency $98.4\% < E$ (11)

These dimensionless magnitudes are suited very well to describe the physical boundaries of a sampling criterion but they are not suited for use in the common practice of indoor aerosol sampling, because the two parameters depend both on the particle size and the suction velocity.

This makes it impossible to characterise either the aerosol or the sampling instrument with these magnitudes. For several sampling instruments Agarwal plotted the cut-off particle diameter in the graph. It is seen that all instruments are said to sample correct beyond the inertial limit of Davies.

In practice of measuring dust concentrations, it is asked: "What is the aspirating efficiency of a certain sampling device?". This means that we are interested in graphs of aspirating characteristics (= aspirating efficiency as a function of particle size) of different sampling nozzles. This was recognized by Kaslow and Emrich (1974), who made a very usefull graph of the sampling efficiency as a function of two dimensionless magnitudes which are independent with respect to the particle diameter and the diameter of the sampling tube. (figure 2) From their graphs the aspirating characteristic can be found easily for different sampling tubes.

The dimensionless magnitudes are:

Tube size number : $$m_{rQ} = \left(\frac{4\pi g^{1/2}}{Q}\right)^{0.4} R_o = 4.34\ Q^{-0.4} R_o \quad \text{(S.I.-units)} \quad (12)$$

Particle size number : $$k_{dQ} = k^{1/5} = 4470\ Q^{-0.1}\ d_p \quad \text{(S.I.-units) normal conditions} \quad (13)$$

where k is the Levin number.

Note:

- The tube size number is determined fully by the sampling device. Therefore m_{rQ} is a characteristic instrument number.
- The particle size number hardly depends on the volume flow.

In figure 2 the tube size number, m_{rQ} and the particle size number, k_{dQ}, are plotted along the axes. The dashed sloping lines give the direction for constant values of Stk_o and $\frac{v_s}{u_o}$ or their equivalent magnitudes

$$m_i = \left(\frac{2}{Stk_o}\right)^{1/3} \quad ; \quad m_g = 2\left(\frac{v_s}{u_o}\right)^{\frac{1}{2}} \qquad (14), (15)$$

These are the directions of resp. the inertial limit ($Stk_o = 0.016$ or $m_i = 5$) and the gravity limit ($\frac{v_s}{u_o} = 0.04$ or $m_g = 0.4$) of Davies criterion, which is fullfilled on the shaded area.

Modified Criterion for Representative Sampling

The criterion of DAVIES (1968) has met considerable critism based on experimental results [AGARWALL (1975), BIEN and CORN (1971), BRESLIN and STEIN (1975), GIBSEN and OGDEN (1977)]

~~Besides these experimental results there is strong theoretical evi-~~dence which leads to a modified criterion. The theoretical considerations, which take into account the direct interaction of particles with the wall of the sampler, are reported to the ECSC. (KUILE, 1977)

The modified criterion for representative sampling is graphed in figure 3 as:

The efficiency is greater than 90 % on a region which is limited by: gravity limit: $m_g < 0.5$ dynamic limit: $k_{dQ} < 0.63$ inertia limit: $m_i > 0.5$	(16)

Because the inertial limit is much lower in this modification, the dynamic limit must be taken in account too, so that in figure 3 the two sampling criteria of Levin and Davies are unified in one sampling criterion, bounded by three lines of different physical nature. From figure 3 the suitability of a sampler for a certain type of dust is easily determined, because each sampler is characterized by its m_{rQ}-value. The m_{rQ}-value determines the physical nature of the limitation:

$m_{rQ} < 0.4$	inertia limit
$0.4 < m_{rQ} < 0.8$	dynamic limit
$0.8 < m_{rQ}$	gravity limit

For each m_{rQ}-value the sampling characteristic is given by the values of the efficiency along a line parallel with k_{dQ}.

Figure 4 gives sampling characteristics which were calculated by Agarwall (1975) for a vertical tube with the inlet upward. This kind of information is needed in common practice. The three sets of sampling characteristics typically represent the three regions of inertial, dynamical and gravitational limitation. In figure 4A for $m_{rQ} < 0.40$ the efficiency is limited by mpaction on the wall. In figure 4B for $0.30 < m_{rQ} < 0.80$, the dynamic limitation is obscured by impaction on the wall of the tube, vertical below the entry. The efficiency is bounded by the dynamic limit only when there is no obstruction vertical below the entry, within a distance l_o. In figure 4C the gravitational influence is clearly visible and results in an efficiency of $E = (1 + \frac{v_s}{u_o})$ 100% for big particles.

COMPARABLE SAMPLING

To meet the two mentioned requirements for comparable sampling of "total dust", first the direction of the inlet is observed, because the cut-off particle diameter strongly depends on this direction. (figure 5)

For $\theta = 0^o$ (upward entry) the efficiency does not fall off to zero beyond the gravity limit. Therefore the upward entry is not suited for comparable sampling. For $\theta = 90^o$ (horizontal suction) the efficiency is reduced by sedimentation on top of the sampler and is highly influenced by horizontal air currents in the neighbourhood. Therefore Davies defines calm air in an environment where the local air currents, w , have velocities less than 1/5 of the suction velocity : $w < 0.2\ u_o$ (wind velocity).

Then for the agreed suction velocity of 1.25 m/s, the wind velocity should be less than 25 cm/s. Whereas in industrial enveronment normal air currents have velocities over 1 m/s, resulting in a suction velocity of at least $u_o = 5$ m/s. The main shortcoming of horizontal suction for comparable sampling is, that there is no well defined gravity limit, because principally beyond the gravity limit $m_g = 0.5$, the efficiency remains about 100% if $w = 0$. But low wind velocities may double or halve this percentage. Therefore horizontal sampling is incompatible with each of the two requirements for comparable sampling.

For $\theta = 180^{\circ}$ (downward entry) the efficiency is sharply bounded on all three boundaries (fig 6). The gravity limit is determined by the outer diameter of the inlet. There is no sedimentation on the wall and therefore if $m_{rQ} > 0.3$, the shape of the inlet is less critical and if $0.3 < m_{rQ} < 0.9$ then the efficiency(96%) is also higher than for the upward entry, because no impaction on the tube below the entry is possible. There are even more advantages of vertical downward sampling, like : - no influence of wind direction.

- least sensitive to horizontal wind velocities.
- least dependent on the shape of the entry.

This all makes vertical downward sampling most promising for standardisation. The only drawback in practice is, that the particle diameter range for an efficiency of 96%, is limited to about 100 µm on the dynamic boundary, depending little on the volume flow. But when particles bigger than 100 µm are sampled from calm air in other directions, they are measured inaccurately, either because they fall into an orifice or they may be blown into. In both cases the concentration is measured inaccurately. The dynamic limit is the fundamental limit for accurate sampling from calm air.

For comparable sampling with a number of different instruments with inverted inlet, the sampling characteristic of all instruments should be determined by the same physical principle. Then for geometrical uniform entries the sampling characteristics will fall off along uniform curves and they are the same when the cut-off particle diameter is the same. The cut-off particle diameters for an efficiency of 96% may be expressed in $(v_s)_{max}$ for the three regions:

m_{rQ}-Region	physical limitation	Formal Limit	sed. velocity for cut-off paricle diam.	
$m_{rQ} < 0.3$	inertial	$(Stk_o)_{max} = 16$	$(v_s)_{max} = 169 \frac{D_o}{u_o}$	under normal conditions
$0.3 < m_{rQ} < 0.9$	dynamical	$(k_{dQ})_{max} = 0.55$	$(v_s)_{max} = 0.45\ Q^{0.2}$	(P=1bar, T= 293 K)
$0.9 < m_{rQ}$	gravitational	$(\frac{v_s}{u_o})_{max} = 1/16$	$(v_s)_{max} = 1/16\ u_o$	$v_s = 3\times10^7 d_p^2$

From this table it appears that for two inverted samplers with different values of m_{rQ} both below the inertial limit (both $m_{rQ} < 0.3$) the cut-off particle diameters are the same if the value of $\frac{D_o}{u_o}$ is the same for each of the samplers. Then the samples are comparable.

Therefore, samples taken with different, geometrical uniform samplers, are comparable within each of the three m_{rQ}-regions, if the following conditions are met:

m_{rQ}-region	Condition
$m_{rQ} < 0.3$	$\frac{D_O}{u_O} =$ const.
$0.3 < m_{rQ} < 0.9$	$Q =$ const.
$0.9 < m_{rQ}$	$u_O =$ const.

I hope that this knowledge will contribute to the standardisation of orifices comparable sampling.

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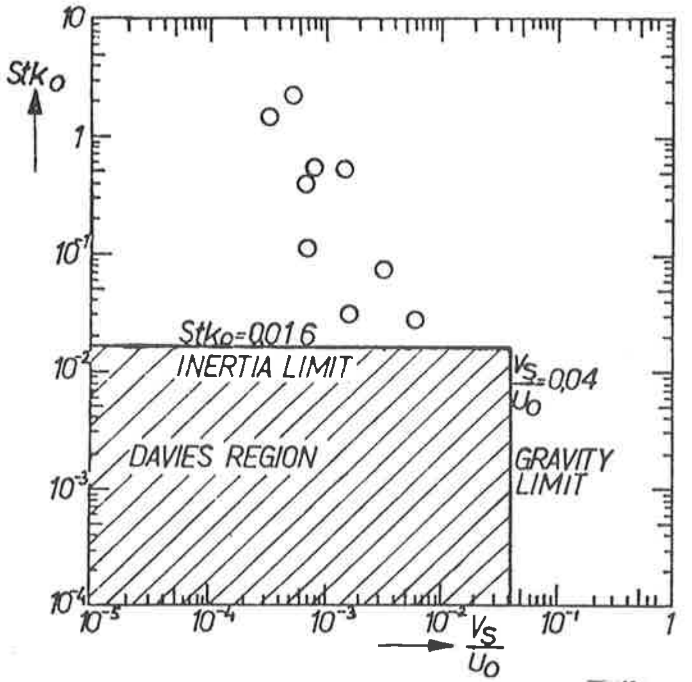

Figure 1

Davies' criterion for representative sampling in the $\left(Stk_o, \frac{v_s}{u_o}\right)$-plane. Circles represent the cut-off particle radii off some commonly used dust sampling instruments. They all are beyond DAVIES' inertia limit. In this graph the magnitudes Stk_o and $\frac{v_s}{u_o}$ are plotted along orthogonal axes. This is not correct, because Stk_o and $\frac{v_s}{u_o}$ are not independent

$$\left(Stk_o = \frac{\tau u_o}{D_o} = \frac{v_s u_o}{g\ D_o} \right)$$

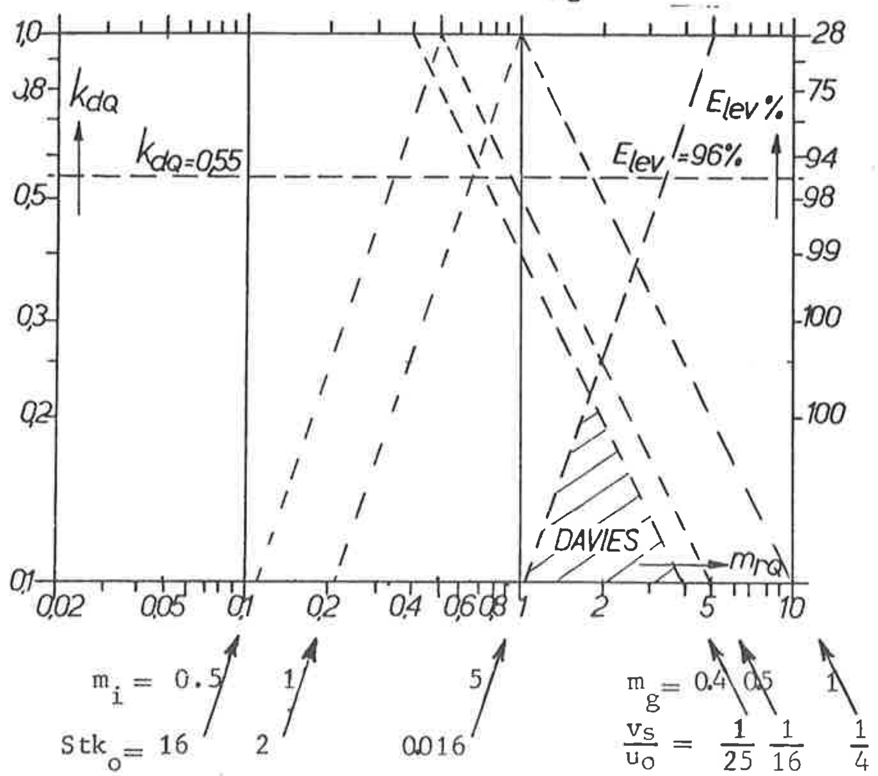

Figure 2

Davies' criterion for representative sampling in the $\left(k_{dQ}, m_{rQ}\right)$-plane. The particle size number, k_{dQ} is proportional with the particle diameter. The tube size number, m_{rQ}, is proportional with the diameter of the sampling tube. This is a characteristic instrument-number, so that each sampler can be characterised by its m_{rQ}-value and its sampling direction.

In this graph, the influence of gravity is constant along the sloping dashed lines for constant values of the gravity parameter, m_g. The influence of inertia is constant along the sloping dashed lines of the inertia parameter, m_i. The Levin efficiency, E_{lev}, is constant for constant values of k_{dQ}.

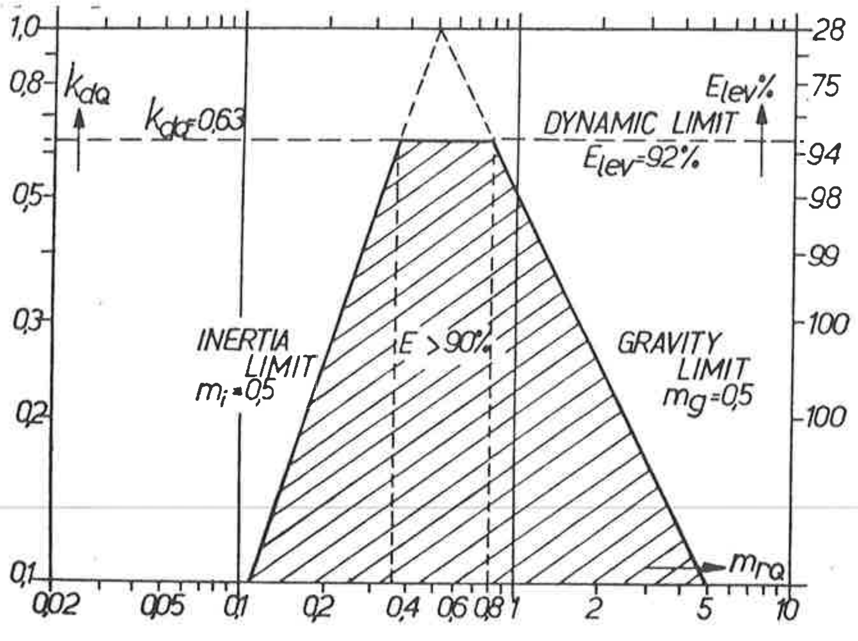

Figure 3

The Modified Criterion for Representative Sampling.

For each sampling instrument the mrQ-value determines the physical nature of the limitation.

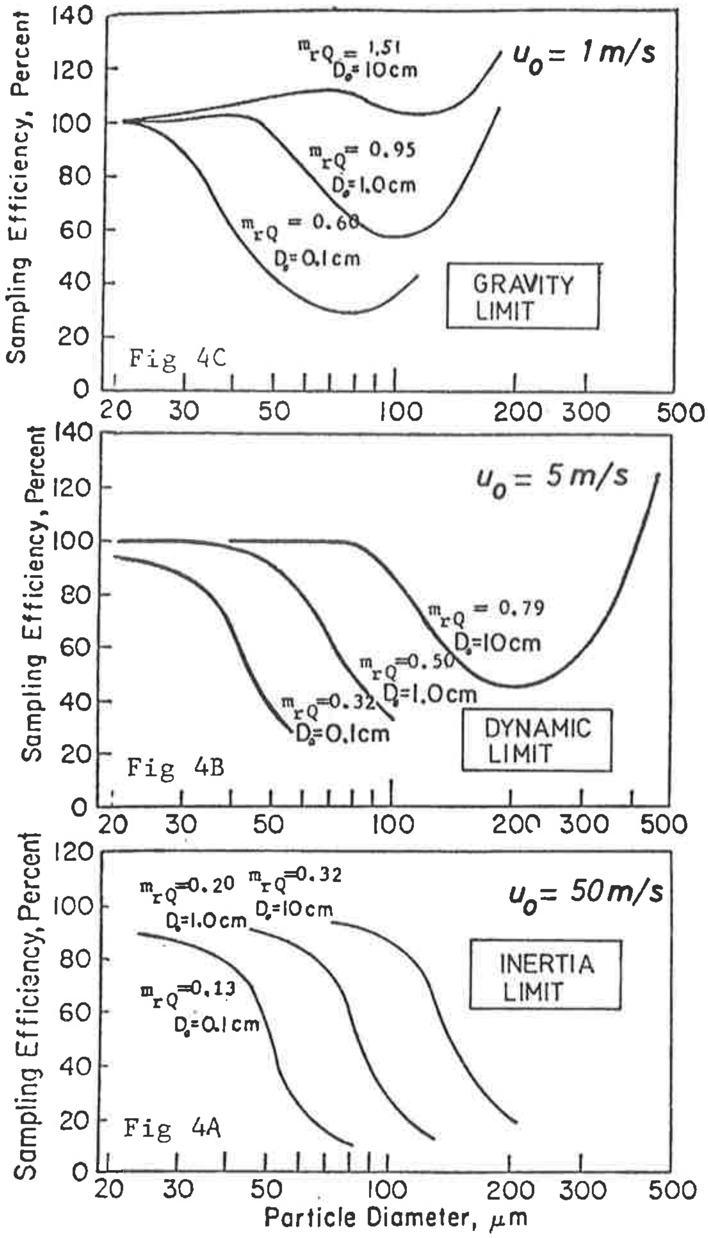

Figure 4 (Agarwal)

Aspirating characteristics for tubes with upward inlet for different m_{rQ}-values in the three regions of different physical limitation.

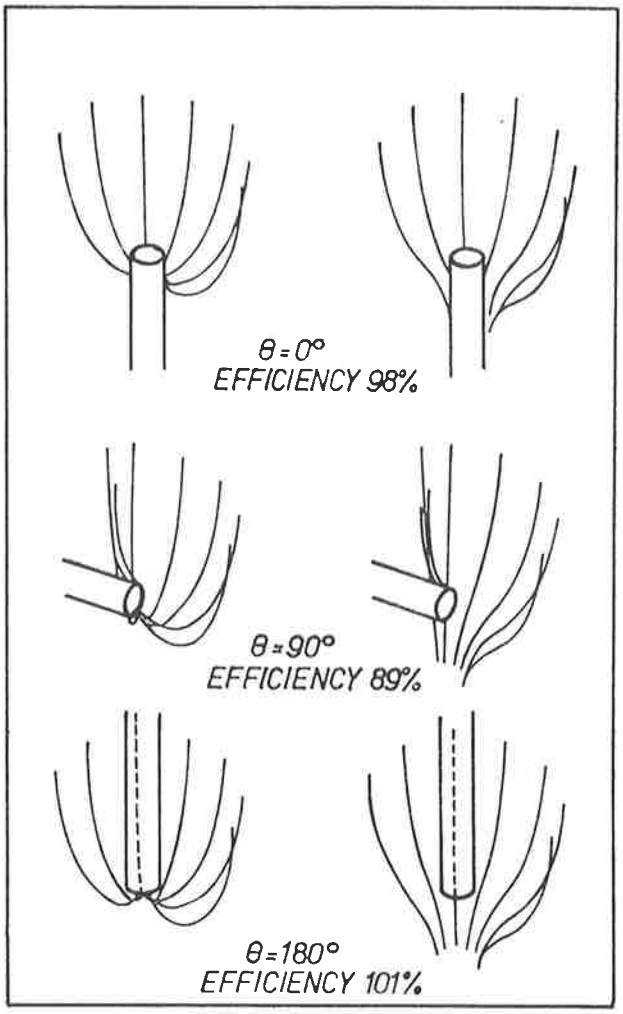

Figure 5 (Kaslow and Emrich)

The aspirating efficiency strongly depends on the direction of the inlet.

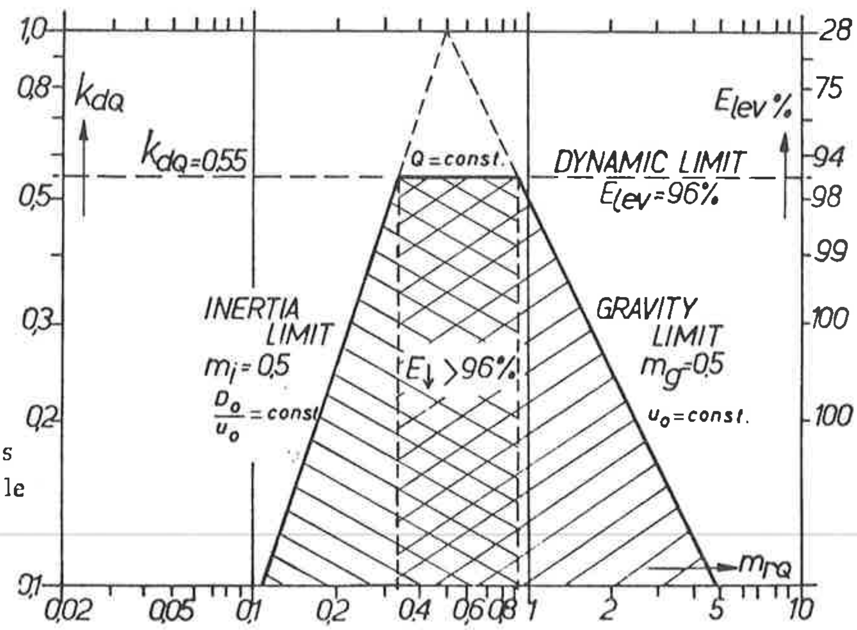

Figure 6

Criterion for Comparable Sampling with different instruments, with the conditions for a constant cut-off particle diameter in each region.