days indicated 15.3% of the tracer was associated with the container—a serious loss.

Flameless aas is unable to give a meaningful analysis for total mercury if the major fraction of the element is associated with particulate phases. However, storage of the samples for eight days at pH <1 with nitric acid allows total mercury to be properly determined. In some water samples, this procedure may not convert all of certain organomercurials to analyzable form. Filtration of samples upon collection requires that the analysis performed on the filtrate not be termed total.

That mercury should associate with the large surface area available in the turbid bay water is not totally unexpected. But that almost quantitative association of mercury with particulates is found in clean, glacial meltwater is surprising. Figure 2 shows a similar tracer experiment performed on acidified glacial ice meltwater. The sample was obtained from a depth of 57 meters at the Camp Century, Greenland site, and had remained frozen until just prior to addition of the radiotracer. The mercury is almost quantitatively associated with the filterable solids, but is released into solution during storage at a pH <1.

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Power Efficiency for Dust Collection

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■ A power efficiency for dust collection devices is introduced for their evaluation in addition to the well-known collection efficiency. Based on the second law of thermodynamics, the power efficiency is not to exceed 100%. Power efficiency of available devices indicates great possibilities for further improvements.

When dust collection devices are compared, the practice has been to list the pressure drop of the gas and that of the liquid if used, utilities in power per 1000 cfm flow, and liquid per 1000 cfm such as given by Sargent (1969). Cyclone separators may even give the impression of having no power consumption. It is readily seen that:

- 1 in. of water pressure drop of gas is equivalent to $(0.118/\eta_b)$ kW/1000 cfm; η_b is blower efficiency.
- 1 hp/1000 cfm is equivalent to 0.746 kW/1000 cfm
- 1 gpm of water consumed is equivalent to 60 [($/gal of water)/($/kWh of electricity)]kW
- 1 psi pressure drop in 1 gpm liquid pumped is equivalent to $(0.435/\eta_p)$ W; η_p is pump efficiency
- 1 lb/hr of steam consumption is equivalent to 0.075 kW.

For comparison on a common basis, the following cases are examples (Sargent, 1969):

With the cyclone separator for 5-μ particles at 95% collection efficiency (percent by mass), 4-in. water pressure drop, assuming a blower efficiency of 80%, the equivalent power is 0.59 kW/1000 cfm.

With the venturi scrubber for 0.5-μ particles at 99% collection efficiency, 20 in. water pressure drop in the gas, 20 psi pressure drop at 6 gpm water flow, assuming a blower efficiency of 80%, water at $1.05/1000 gal., power at $0.02/kWh, 5% loss of water, and pumping efficiency of 80%, the equivalent power consumption is: 2.95 + 0.07 + 0.39 = 3.41 kW/1000 cfm.

With the electrostatic precipitator for 2-μ particles at 99% efficiency, pressure drop 0.5 in. water, and 0.3 kW of electricity/1000 cfm, the equivalent power consumption is 0.074 + 0.3 = 0.374 kW/1000 cfm.

Hence users and builders of equipment for the removal of particulate matter from a gas are interested in:

- a strict reference parameter for comparing available equipment in addition to collection efficiency
- the basic reason for the energy required in collection
- the ultimate realizable limit of energy requirement for dust removal from a given suspension.

Hence, besides collection efficiency based on mass as mentioned above, it is desirable to identify a power efficiency as in gas separation which is based on minimum work of separation (Ruhemann, 1949). For this purpose a modified Gibbs (1878) relation for entropy of mixing (Δs) per unit mass of gas is introduced, which gives the minimum work for separation at low dust loading as:

$$w_m = T\Delta s = (D + D_t)(C/\lambda)x_p[\eta_c(1 - \ln x_p) + (1 - \eta_c)\ln(1 - \eta_c)] \quad (1)$$

for a unit mass of the gas (note that for η_c = 100%, $y \ln y \rightarrow 0$, as $y \rightarrow 0$). In this relation, D is the molecular diffusivity, D_t is the turbulent diffusivity, C is the mean speed of gas molecules, λ is the mean free path, η_c is the collec-

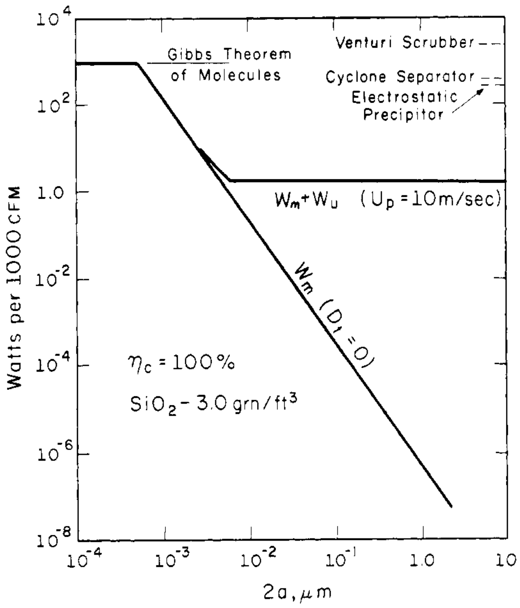

Figure 1. Minimum power for collecting 3 grains/ft^3 silica of various sizes in comparison to power requirements of practical devices; power input in W/1000 cfm airflow

tion efficiency, x_p is the mole fraction of particles which, for monodispersed spherical particles, is given by,

$$x_p = (m_p/m_g)(M_g/M_{pa}) \quad (2)$$

where m_p/m_g is the mass ratio of particles to gas in a given volume, M_g is the molecular weight of gas and $M_{pa} = N_0(4\pi/3)a^3\overline{\rho_p}$, N_0 is the Avogadro number, a is the particle radius, and $\overline{\rho_p}$ is the density of materials constituting the particles. It is seen that for a static suspension, $D_t = 0$, $DC/\lambda = RT$ is a gas constant, and T is the absolute temperature of the gas based on the original reasoning of Gibbs.

A distribution in a particle size is given by a number distribution function $f(a)$, such that

$$n\int_{a_1}^{a_2} f(a)da = n \quad (3)$$

where n is the number per unit volume of particle cloud, and a_1 and a_2 are the lower and upper limits of particle radii. The distribution in mass is therefore given by $(4\pi/3)a^3\overline{\rho_p}f(a)$, and the mole fraction of particles of radii over the range a and $(a + \Delta a)$ is given by:

$$x_{pa} = (M_g n/N_o m_g)f(a)\Delta a \quad (4)$$

and the overall mole fraction of particles is

$$x_p = \sum_a x_{pa} = (M_g n/m_g N_0)\int_{a_1}^{a_2} f(a)da \quad (5)$$

and n is given by the total mass of particles per unit volume of the cloud by:

$$m_p = (4\pi/3)\overline{\rho_p} n\int_{a_1}^{a_2} a^3 f(a)da \quad (6)$$

The entropy of mixing of such a dilute suspension is:

$$\Delta s = -R\Sigma x_{pa}\ln x_{pa} + Rx_p = (M_g n/m_g N_0)R\{[1 - \ln(M_g n/m_g N_0)]\int_{a_1}^{a_2} f(a)da - \int_{a_1}^{a_2} f(a)\ln f(a)da\} \quad (7)$$

For a narrow size distribution, the distribution function can be represented by a Gaussian form as given by Soo (1967):

$$f_0(a) = [(2\pi)^{1/2}\delta]^{-1}\exp[-(a - \bar{a})^2/2\delta^2] \quad (8)$$

such that the range of a can be approximated by: $-\infty < a < \infty$, δ is the mean deviation, and $\bar{a}$ is the mean size.

For particles with normal size distribution at 100% collection efficiency and $D_t = 0$, we get:

$$\Delta s = R\overline{x_p}[(3/2) - \ln\overline{x_p}] \quad (9)$$

where $\overline{x_p}$ is the mean mole fraction based on particles $\bar{a}$ such that

$$x_{pa} \equiv \overline{x_p}f_0(a)\Delta a \quad (10)$$

For a dynamic system with particle velocity U_p, an additional excitation to be removed from the particles is given by work (Soo, 1967) in the amount of

$$w_u = m_p{}^* U_p{}^2/2 \quad (11)$$

per unit mass of fluid; $m_p{}^*$ is the mass ratio of particles to fluid.

A typical relation is shown in Figure 1 for silica particles at 3 grains/ft^3 and 100% collection efficiency in a flowing gas. It is seen that D_t is rarely more than 100 times that of the molecular diffusivity in a closed system. Figure 1 shows that most of the collection devices work on the basis of "overkill" power consumption. A great deal of improvement can be expected with additional understanding obtained from basic research.

The power efficiency is given by:

$$\eta_p = (W_m + W_u)/(\text{actual power input}) \quad (12)$$

where $W = w$ in the above expressed in units of power input.

It is seen that even including the flow excitation of 10 m/sec, D_t / 100 D, 1-μ particles in an electrostatic precipitator has W_u = 1.74 W/1000 cfm and $W_m = 10^{-4}$ W/1000 cfm flows. Hence for an actual power consumption of 374 W/1000 cfm, the power efficiency of the above-mentioned electrostatic precipitator is no more than 0.46%, and the cyclone separator has an efficiency of 0.3%. Entropy of mixing is significant for particles below 10^{-2} μ size.

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