AN APPARATUS FOR THE MAINTENANCE OF A
CARBON DUST CLOUD OF CONSTANT CONCENTRATION

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During the course of an investigation of the health risk due to charcoal dust, it became necessary in
connection with animal experiments to produce and maintain a cloud of charcoal containing a trace
element of concentration and particle-size corre-
sponding to that found under factory conditions.
Animals were to be placed in the cloud for a
considerable daily period extending over some
months, and in order to estimate the dosage applied it was necessary to control the cloud concentration
automatically. An apparatus was developed to
fulfil these conditions, and as it may have a wider
application for the purpose of maintaining a constant concentration of many other types of
particulate cloud over a long period, it is described in detail. The physiological work has been com-
pleted and is the subject of an internal report of the
Ministry of Supply.

Considerations of Cloud Production Method

The accurate determination of the optical size
distribution of a cloud of carbon particles in
which a considerable degree of aggregation exists is a matter of extreme difficulty and uncertainty.
The cascade impactor was used as a comparative
instrument, samples being taken of the factory
cloud, the relative densities of the deposits on the
four graded plates being used as standards. Samples
of the experimental cloud could then be taken and
compared with the standards, and the particle-
size of the cloud adjusted in the appropriate manner.
The apparatus used, therefore, had to fulfil the
following conditions:

(a) to simulate the factory cloud the particle-size
range must be such that when the cloud is
sampled with the cascade impactor, at a
flow-rate of 17.5 litres per minute, almost
all the deposit is found on the third and
fourth plates.

(b) sufficient cloud must be produced to maintain
a concentration of 250 mgm. per cu. m. of
carbon in a chamber of 7.8 cu. m.

(c) the apparatus should be capable of maintain-
ing the cloud for at least 7 hours before
recharging with charcoal is necessary.

(d) The apparatus should be simply controllable
in order to facilitate the application of a
suitable regulating device to ensure con-
stancy of cloud concentration.

(e) In order to ensure the continuity of the experi-
ment from the physiological viewpoint the apparatus must be comparatively
trouble-free over a period of 700 hours at
7 hours per day on a 6-day week basis.

Method of Cloud Production

The apparatus finally developed is shown in fig. 1. The cloud is produced by the attrition of charcoal
in the rotating drum, which is enclosed by the hood,
and is then blown into the cloud chamber as shown
by the arrows on the figure. The drum consists of a
cylinder of 8 inches diameter and 10 inches length,
the side being made of 22 mesh 26 S.W.G. copper
gauze, and the end plates of ½ inch thick sheet iron.
Inside the drum the three radial vanes pour the
charcoal and produce attrition as the drum rotates.
The drum rests upon rubber-covered rollers, one
of which is rotated by means of an electric motor.
The second roller is merely an idle rotating support.
The enclosing hood is fitted with an air intake and
exit, the former being connected to the centrifugal
blower drawing its supply of air from the cloud
chamber. The exit rises vertically for 9 inches and
is then led horizontally into the cloud chamber.
This vertical rise is designed to remove the larger
particles by elutriation, and the horizontal section
performs the same function by sedimentation.
Since the air supplied to the drum is derived from
the cloud chamber and therefore contains con-
siderable carbon cloud, the drum mechanism is
enabled to maintain higher concentrations in the
cloud chamber than would otherwise be possible,
i.e., the system is regenerative. The drum is taken
out through one side of the hood, which is detach-
able, and charged with charcoal after the removal
of one end plate. The normal charging of granules is
approximately one-third of the volume of the
drum, the granules being of the order of 1.84 mm.
in diameter. Debris from the ground charcoal is
sieved through the side of the drum and accumu-
lates on the floor of the hood; this has to be
removed at about 20-hour intervals.

Particle-size Distribution. As described in the
previous paragraph, favourable conditions are
obtained for the removal of the larger particles in
the cloud by elutriation and sedimentation. A
comparatively sharp cut-off is obtained on the
maximum particle-size by control of the air stream
velocity, varied by adjustment of a series resistance in the centrifugal blower circuit. This was adjusted until an accurate simulation of the size distribution of the factory cloud was obtained.

Control of Output. Since for the purpose of animal experiments the required cloud concentration was about three times the factory peak conditions, and since it was also desired to use only one drum for economy and simplicity, it was essential to achieve the maximum output. As the speed of rotation of the drum increases there is a progressive rise in output due to increasingly violent pouring and churning of the charcoal granules. On reaching some critical speed, centrifugal forces begin to take control and prevent the pouring from taking place, the system tending to rotate as a rigid whole, and causing a rapid diminution in output. Fortunately, the onset of the centrifugal effect is made apparent by a change in the sound emitted by the drum. It was therefore a simple matter to adjust a series resistance in the motor circuit to give to optimum speed of rotation for maximum output. A difficulty arose due to the drum motor being unable to start unaided from rest with the resistance adjusted as described above. Since regulation of cloud concentration was achieved by automatic switching of the drum motor at frequent intervals, this difficulty had to be overcome, and was obviated by temporarily short-circuiting the control resistance on starting. The device used is shown in fig. 2. When the regulator closes $S_1$, current flows directly to the motor through the closed mercury switch $S_2$. At the same time the solenoid is energized and withdraws the iron plunger from the mercury, and immediately mercury begins to flow from the reservoir, through the capillary, equalizing the level in the two arms. Conditions can be arranged so that after 10 to 12 seconds the level falls below the upper contact $S_3$, thus breaking the circuit.

Fig. 1.—Diagram showing drum and roller. (Hood shown in dotted lines.)
The motor then receives its supply through the control resistance R, and this state continues so long as S₁ remains closed. On S₁ opening, the plunger falls, closing S₂, and the device is reset for a fresh cycle of operation.

The Requirements for the Regulator

For the purpose of physiological experiments, and having due regard for the probable accuracy of routine chemical estimation, it was decided that stabilization of cloud concentration to within ± 5 per cent. of the required value would be sufficient. The simplest method of achieving this result is to switch the drum motor on and off at suitable intervals in the manner of a thermostat heater. The controlling element chosen was a photocell in conjunction with a source of constant illumination, arranged so that the cloud obscured some of the light from the lamp before reaching the photocell. The photocell current then depends on the optical density of the cloud. The limitations of this controlling element depend principally on the degree of constancy obtainable in the light source; experiment shows that a 75-watt lamp bulb driven by a 150-watt 'Advance' constant voltage transformer exhibits maximum fluctuations of about ± 3 per cent. in candle-power with normal A.C. supply mains fluctuations. The equivalent change in cloud concentration to produce the same change at the photocell is approximately ± 3 per cent., and so for the differential cloud concentration to be not greater than ± 5 per cent. the drum motor should be switched with about 2 per cent. change in illumination of the photocell. In practice this necessitates considerable amplification between the photocell and the relay controlling the drum motor. These considerations led to the design of the photocell relay described in the next section.

The Regulator. The optical system of the regulator is very simple, consisting only of a 75-watt lamp...
bulb, a portion of whose filament is focused with a single condenser lens on to the photocell, about 1½ metres distant. The circuit diagram of the complete regulator is shown in fig. 3. $T_1$ is an 'Advance' 150-watt constant voltage transformer of 230 volts output, $V_1$ is the photocell, $V_2$ the amplifier, $V_3$ a thyatron, and $S_1$ a hot wire vacuum relay whose contacts control the drum motor through the starting switch $S_2$. The operation of the circuit can best be described by assuming some light to fall on $V_1$, and considering the state of affairs at successive A.C. half-cycles. Take first the half-cycle when $B$ is positive and $A$ negative. $V_1$ passes current producing a voltage drop across $R_1$ so that the top plate of $C_1$ is negative with respect to the bottom plate. The time constant $R_1C_1$ is long compared with $1/50$th second, so that the voltage across $C_1$ remains practically constant over one cycle.

Now consider the next half-cycle when $A$ is positive with respect to $B$. $V_2$ now conducts, and its grid bias is controlled from three sources—and hence its anode current depends on three factors. Negative A.C. bias is derived from $R_7$, $R_8$; positive A.C. bias is derived from $R_9$, $(R_3 + R_4 + R_5)$, and this is variable; negative D.C. bias is derived from $R_6C_2$ controlled by $V_3$ as described above. The two A.C. biases partially counter-balance one another and are used so that $R_2$ may be made large to obtain a large voltage output from $V_1$. The anode current of $V_2$ produces a voltage drop across $R_8$ charging $C_2$ with the polarity shown in fig. 3, and the time constant of $R_8C_2$ is again large compared with $1/50$th second.

Now consider the next half-cycle when $B$ is again positive with respect to $A$. $V_3$ now conducts over part of the half-cycle—as controlled by the voltage across $C_2$—and the resulting anode current will flow through the hot wire control of $S_2$. Obviously at some value of anode current through $V_3$ the switch $S_2$ will close, thus turning the drum motor on, and this point is controlled by the grid bias of $V_2$. Thus by adjustment of $R_4$ and $R_6$, 'fine' and 'coarse' respectively, the additional D.C. bias required from $V_1$ to close $S_2$ can be varied, and hence the cloud concentration at which $S_2$ opens and closes can be varied at will. In other words the cloud concentration can be varied by adjustment of $R_4$ and/or $R_6$ after which it will be stabilized at the new concentration without further adjustment of the apparatus.

On striking, $V_3$ takes appreciable grid current which tends to charge $C_2$ with polarity the reverse of that shown in fig. 3. If $R_5 = 0$, then at the firing point the grid current of $V_3$ is more than the anode current of $V_2$, so that the latter current must be increased to a greater value than $V_3$'s grid current before $S_2$ can open. In practice this means that there is some 'backlash,' i.e. the opening and closing illuminations are somewhat different. This 'backlash' or differential can be reduced or eliminated by making $R_5$ large. In practice it was found desirable to make $R_9$ variable so that the on/off period could be partially controlled. With no 'backlash' (i.e. $R_9$ very high) a change of illumination of about 0·2 per cent. was required to operate $S_1$, and since there were continual small fluctuations in the illumination, $S_1$ was opened and closed as often as once in two or three seconds, which was inconveniently frequent. The operator must strike a balance between too little 'backlash,'
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The regulator has been in continual use for four months and has performed for about 700 hours. In that time one switch (S₁) has failed (it was in poor condition initially), one lamp has failed, one thyatron (V₃) has failed, and one resistance (probably initially faulty) has failed. Apart from these failures the only attention the regulator has required has been periodical cleaning of the lamp bulb. In use this became sooted over with charcoal, reducing the illumination, and hence the cloud concentration. No really satisfactory static self-cleaning device was developed, but something in the nature of a motor car wind-screen wiper would have been convenient. For the major portion of the running period the regulator was unattended.

Fig. 4 shows the general layout of the apparatus in diagram form. Details of the drum are shown in fig. 1, the starter switch in fig. 2, and the photocell amplifier and relay in fig. 3. The rest of the diagram is self-explanatory. A perspective view of the complete apparatus is shown in fig. 6. Fig. 7 shows a view of the cloud chamber, the animals being placed on wire netting shelves.

A Simple Check Photometer

It was thought desirable to have a check upon the absolute cloud concentration which might change due to the relative movement of the lamp and photocell on cleaning. In a more rigid optical arrangement this could perhaps have been avoided. To provide such a check a simple linear photometer was designed and constructed, the circuit diagram of which is shown in fig. 5. Additionally, the check photometer could be used to maintain the cloud with manual switching of the drum motor in the event of regulator breakdown.

V₈ is a photocell identical with V₁ and viewing the same lamp (fig. 3) through a portion of the cloud. Before starting the regulator each morning the meter M (50μA, 1500ω) was adjusted to zero with R₁₅ (i.e. with no cloud). Then on production of cloud the illumination on V₈ fell, producing a

\[ V₄ = 6J7G \text{ (TRIODE CONNECTED)} \text{ Am.} \]
\[ V₅ = 6J7G \text{ (TRIODE CONNECTED)} \text{ Am.} \]
\[ V₆ = OSRAM H 63. OR Am. 6F5G. \]
\[ V₇ = MULLARD 7475. \]
\[ V₈ = MAZDA P.E. 8. \]

\[ R_{11} = 5 \text{ MΩ.} \]
\[ R_{12} = 0.05 \text{ MΩ.} \]
\[ R_{13} = 0.03 \text{ MΩ.} \]
\[ R_{14} = 0.075 \text{ MΩ.} \]
\[ R_{15} = 0.025 \text{ MΩ.} \]
\[ R_{16} = 0.015 \text{ MΩ.} \]
\[ R_{17} = 0.01 \text{ MΩ.} \]
\[ R_{18} = 0.003 \text{ MΩ.} \]

Fig. 5.—Check Photometer.
change of voltage at \( V_4 \)'s cathode, and hence an arbitrary reading on \( M \). The cloud was adjusted by alteration (if required) of \( R_4/R_5 \) (fig. 3) until the regulator stabilized the cloud at a fixed but arbitrary reading of \( M \). \( V_4 \) and \( V_7 \) provided a stabilized high tension voltage derived from the D.C. mains supply, which is further stabilized by the cathode follower connection of \( V_4 \) and \( V_5 \) so that variations in the supply input voltage are reduced by a factor of about 2000 before being applied to the meter.

**Performance**

Samples of the cloud were taken on filter paper and the concentration found by estimation of the trace element. In separate experiments the trace element/charcoal ratio was determined for (a) supply, (b) the sieved debris and (c) the sedimented cloud. The ratio was found to be sensibly constant within the limits of estimation error, showing that no alteration of the trace element/carbon ratio had taken place. In practice a sample was taken on each day's run as a check on the absolute concentration. In addition, pairs of samples were taken at hourly intervals on each of three days to check the performance of the regulator. A statistical analysis of the results showed that the required aim of \( \pm 5 \) per cent. in the cloud concentration was achieved.

In addition to the regulator failures mentioned previously, in 700 hours one drum side was worn out and replaced by a spare, and the rubber of the rollers was renewed once. None of the failures was serious, the only fault causing a delay of more than a few minutes running time was the breakdown of the rubber rollers. Subsequently it was found that insulation tape was more durable, gave a better drive than rubber and was very much easier to replace. This fault caused a loss of one day (7 hours) in running time, and afforded an opportunity for a general overhaul. Care should be taken to prevent carbon from depositing on the electrical circuits and all apparatus should be earthed and circuits adequately supplied with fuses.

**Results**

The standard deviation \( \sigma \) of the chemical estimation and sampling errors was estimated by taking all samples in duplicate. The standard deviation of the overall variation of the results \( \sigma \) was calculated and hence the standard deviation of the regulator \( \sigma_k \) obtained. The calculated value of \( \sigma_k \) was 2.27. If the normal error curve is assumed, the apparatus

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**Fig. 6.**—Control Chamber.

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**LEGEND**

A. CHECK PHOTOMETER.
B. REGULATOR.
C. CONSTANT VOLTAGE TRANSFORMER.
D. SAMPLING SHELF.
E. SPEED CONTROL RESISTANCES.
F. DRUM MOTOR.
G. HOOD.
H. CENTRIFUGAL BLOWER.
I. MIXING FAN SWITCH.
J. OBSERVATION HOOD.
will be within $\pm 2.27$ pet cent. of its adjusted value for 68 per cent. of the running time, and within $\pm 4.45$ per cent. during 98 per cent. of the running time. As large departures from the mean (except for breakdowns) are impossible, the figure of $\pm 5$ per cent. can be regarded as the outside limit of error.

Summary

An apparatus has been developed for the production of a carbon dust cloud in connection with physiological research on health hazard in charcoal filling factories. The cloud was produced by the attrition of charcoal in a rotating drum, and the maximum particle-size adjusted by elutriation. The drum was driven by a motor switched in the manner of a thermostat heater by a photoelectric relay controlled by the optical density of the cloud. The whole system provided a cloud of concentration $250 \text{ mg./m.}^3 \pm 5$ per cent. in a specially constructed chamber of $7.8 \text{ cu. m.}$ for a period of $700$ hours ($7$ hours/day). The apparatus was largely unattended except for a short daily period of standardization at the beginning of each run, and a second period of a few minutes at midday.

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