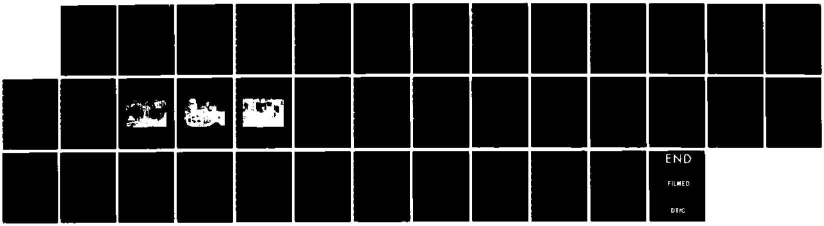
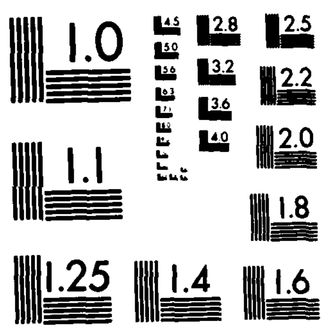
AD-A148 600 LABORATORY SIMULATION OF SMOKE REDUCTION FROM AIRCRAFT ENGINE TEST CELL E..(U) CLEMSON UNIV SC DEPT OF CHEMICAL ENGINEERING R W RICE 22 OCT 84 1/1

UNCLASSIFIED AFOSR-TR-84-1078 AFOSR-83-0147 F/G 13/2 NL



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# REPORT DOCUMENTATION PAGE

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| | |
|---|---|
| 1. REPORT NUMBER: AFOSR-TR- 84-1078 | 2. GOVT ACCESSION NO. |
| 3. RECIPIENT'S CATALOG NUMBER | |
| 4. TITLE (and Subtitle): Laboratory Simulation of Smoke Reduction From Aircraft Engine Test Cell Exhaust Using a Fluidized Bed Filter | 5. TYPE OF REPORT & PERIOD COVERED: FINAL: 01 Jun 83-31 Aug 84 |
| | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s): Richard W Rice | 8. CONTRACT OR GRANT NUMBER(s): AFOSR-83-0147 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS: Dept. of Chemical Engineering, Clemson University, Clemson, SC 29631 | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 2308/D9 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS: AFOSR/NA Bolling AFB DC 20332-6448 | 12. REPORT DATE: October 22, 1984 |
| | 13. NUMBER OF PAGES: 32 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | 15. SECURITY CLASS. (of this report): Unclassified |
| | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

LIGHT-SOURCES
PHOTOCELL DETECTORS
OPTICAL DENSITIES
PERCENTAGE OPACITY REDUCTION (POR)
GRAVIMETRIC MEASUREMENTS
INERTIAL IMPACTOR

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The lowering of aircraft engine test cell exhaust opacity by fluidized bed filtration of soot was simulated in the laboratory. Smoke from a diesel burner was diluted with ambient air and passed through a 25 cm diameter cylindrical bed of either 500 or 1000 micron glass spheres. Bed depths ranging from 2.5 to 10 cm and superficial gas velocities of 2 to 60 cm/s were studied. Using separate light-sources and photocell detectors, the optical densities

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20. Abstract (Continued)

of the bed inlet and outlet gas streams were simultaneously monitored. From these data percentage opacity reduction (POR) values were determined as a function of time. This measure of filtration efficiency was found to increase with bed depth, ranging from roughly 50% for a 2.5 cm deep bed of 1100 micron glass beads to 99% for a 10 cm deep bed of 500 micron beads. No appreciable decline in effectiveness was observed for periods of up to 1.5 hours. Attempts were made to supplement POR results with gravimetric measurements of particle loading and size distribution made using a stack gas sampler (inertial impactor). Although considerably scattered, the latter roughly confirmed the optical measurements and revealed that > 90% of the soot was < 1 micron in diameter. Overall the project demonstrated the potential effectiveness of either fixed or fluidized bed filtration as a simple, economic means of dramatically reducing smoke emissions from aircraft engine test cells.

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## INTRODUCTION

In spite of the short-duration, intermittent operation of military aircraft engine test cells, various air pollution regulatory agencies in the United States currently feel that the exhaust from test cells must comply with stationary source smoke standards developed for power plants and incinerators. Consequently, the U. S. Air Force is interested in cost effective, practical ways to substantially reduce visible smoke emissions from test cells. This report documents a short research effort aimed at assessing the potential of fluidized bed filtration for this purpose.

## BACKGROUND

### 1. Aircraft Engine Test Cells and Emissions

The U. S. Air Force operates over 150 open test stands and over 100 enclosed test cells for engine testing after maintenance or prior to installation in an aircraft (1). As shown schematically in Figure 1, the engine exhaust is directed by the augmentation throat through a draft tube 2 to 6 m (7 to 20 ft) in diameter and 15 to 23 m (50 to 75 ft) in length. Augmentation air at a typical ratio of 2 to 1 (1, 2) is aspirated into the throat and the total exhaust stream from the draft tube is cooled with quench water and deflected upward into the exhaust stack. It is above or within this stack that an air pollution abatement device such as a fluid bed filter would be positioned.

The exhaust contains pollutant gases, e.g., $CO$, $SO_2$, $NO_x$, hydrocarbons, in addition to particulates. "Smoke" is associated with non -transparent gases such as $NO_2$, but the major contribution is made by 0.1 to 1 μm diameter particulates (soot). Techniques considered for reducing soot emissions can be broadly classified as either conversion or separation. Conversion deals with lowering soot concentration by using either 1) fuel additives, fuel atomization/emulsions, etc. (3), to improve combustion in the engine, or 2) an afterburner. Separation methods involve physical removal and disposal of pollutants. Specific separation systems that have been considered include conventional filters, wet electrostatic precipitators, cyclone or impingement separators, and a variety of wet scrubbers. Most, if not all, of these separation schemes are extremely expensive to build and operate, and involve potential problems associated with operability, corrosion and waste water disposal (secondary pollution); thus there is considerable incentive for assessment of alternative smoke-reduction technologies such as the subject of this report.

### 2. Fluidized Bed Filtration

There are numerous books and review articles (4-8) on the theory and applications of fluidized beds, thus only a brief description of the general features will be given here. In a fluidized bed a stream of gas is introduced through a distributor (wire screen, multi-orifice plate, etc.) positioned below a "bed" of solids and passes upward with sufficient velocity such that the upward drag force and motion of the bubbles created partially overcome the gravitational force acting downward on the bed particles. This imparts a liquid-like character to the gas-solid system, which, among other things, gives the advantage of easy solids removal and addition in continuous operation. Due to the

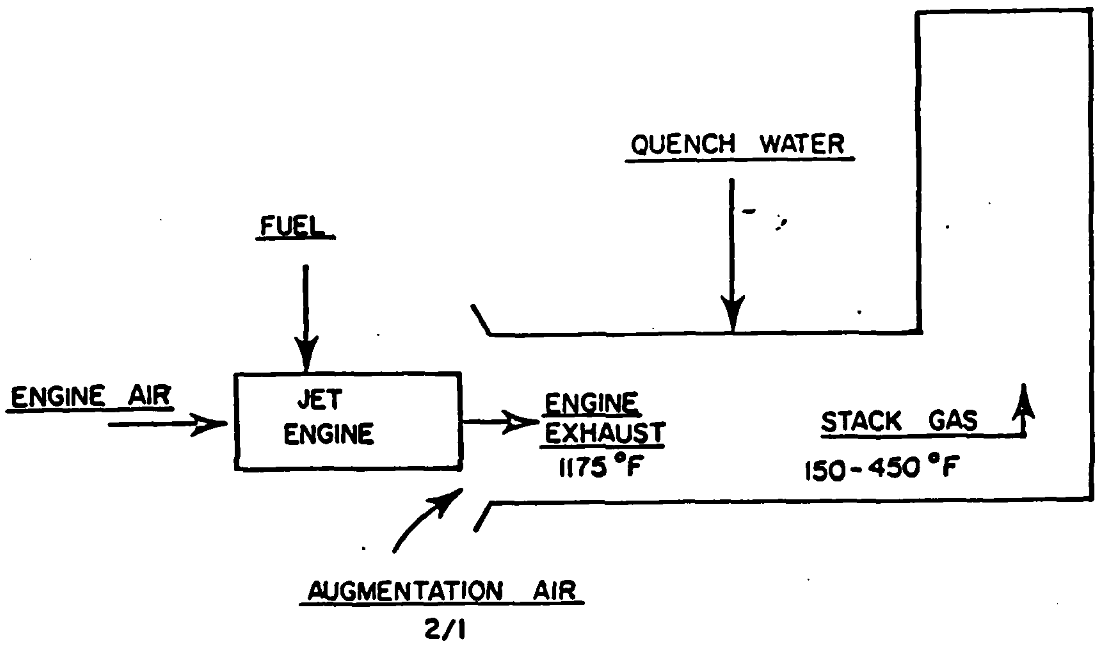


Figure I. Schematic Diagram of a Typical Turbine Engine Test Cell extreme complexity of the fluid mechanics of this system, no satisfactory fundamental theory has been developed so far, but various semi-theoretical models are in use. Most common is the "Two Phase Model" (4-7, 9) in which a bed is pictured as consisting of 1) an "emulsion" phase made up of particles plus interstitial gas and 2) a "bubble" phase made up of gas in visible bubbles. The many parameters involved in a fluid bed influence its behavior primarily through their effect on bubble properties such as size (6, 10), distribution (11), frequency (12), and velocity (7, 11).

It has been established experimentally that a fluid bed can effectively remove fine (<1.5 μm) particles (13-16) and at least one "fluid bed dry scrubber" has been employed on an industrial scale for air pollution abatement (17). McCarthy et al (18), Jackson (13) and Patterson et al (19) studied the use of small, shallow, single and multi-staged fixed and fluid beds of 135-515 μm alumina or glass particles for filtration of 0.06 to 1.4 μm diameter liquid dioctyl phthalate (DOP) aerosols. Single stage filtration efficiencies for 2.5 cm deep stages varied from 42 to 94% depending on aerosol size. Efficiencies of nearly 100% were found for three such stages used in series. Melcher (20, 21) developed a mathematical model and reported data showing that the use of an electric field can improve submicron particulate collection efficiency for a fluid bed filter. An experimental study of electrofluidized bed filtration of charged aerosols has been reported by Tardos and Snaddon (22). In all of these studies, aerosol size, bed particle size, bed height, and superficial gas velocity were important parameters affecting filter performance. Efficiency decreased gradually with increasing gas velocity, increased with increasing bed height, and went through a shallow minimum for roughly 0.5 μm aerosols.

Several theoretical descriptions of the phenomena involved in fluidized bed filtration have been published along with mathematical models relating measurable parameters to predicted collection efficiency (18, 19, 21-28). In general, such modeling involves first considering the various mechanisms by which a particle is collected and, second, modeling the complicated hydrodynamic behavior of the gas-solid fluidication process. For a fluid bed without an electric field the collection mechanisms of possible importance are 1) inertial inpaction, 2) interception, and 3) Brownian diffusion.

Inertial impaction is a mechanism wherein a particle moving with an air stream which flows around a collecting object resists the change in direction and may impact on the collector. The inertial impaction number is the ratio of the distance that a particle will penetrate into still air (when given an initial velocity of $U_o$) to the diameter of the collector, and is given by:

$$\phi = \frac{C U_o \rho_p d_p^2}{18\ \mu d_c} \qquad (1)$$

where: $\phi$ = inertial impaction number

$C$ = Cunningham slip factor

$U_o$ = initial particle velocity, cm/s

$\rho_p$ = density of particles, g/cm$^3$

$\mu$ = gas visocity, P

$d_p$ = particle diameter, cm

$d_c$ = collector diameter, cm

Ranz and Wong (26) have reported inertial impaction efficiencies for spherical collectors as functions of $\phi$ and have shown experimentally that collection is negligible for $\phi < 0.2$. Efficiencies for impaction can be calculated by assuming Stokes law for the particle in an ideal fluid (23), i. e.,

$$\phi = \frac{st}{(st + 0.5)^2} \tag{2}$$

where

$$st = \frac{2\phi}{C} .$$

The interception mechanism is often thought of in combination with inertial impaction, but can be important even when $\phi = 0$. Interception may be pictured as a process involving a massless particle having finite size but no inertia. The center of the particle follows the fluid stream lines, but whenever the center approaches within a distance of $d_p/2$ from the surface of the collector the particle will be "caught." A relationship for target efficiency in terms of the interception number, $N_R$, has been developed (25),

$$N_R = d_p/d_c \tag{3}$$

$$\eta = (1+N_R)^2 - (1+N_R)^{-1} \tag{4}$$

where $\eta$ = collection efficiency.

When inertial forces and particles are small, Brownian diffusion plays an important role in collection. If a particle passes close to a collector, the random, diffusional motion of the particle may bring it into contact with a collector. The efficiency of collection due to Brownian diffusion has been modeled as a function of the Peclet number,

$$N_{pe} = \frac{U_o d_c}{d_{bm}} \tag{5}$$

where $d_{bm}$ = Brownian diffusion coefficient, $cm^2/s$.

Levich (26) has developed an expression for the efficiency of collection for the case of diffusion to a single isolated sphere:

$$\eta = 4.04\ (N_{pe})^{-2/3}. \tag{6}$$

McCarthy et al. calculated theoretical collection efficiencies for each mechanism for a range of aerosol sizes (18) and concluded that for the cases studied impaction contributed very little, interception dominated for larger (0.7 - 1.4 μm) particles, and diffusion was the primary collection mechanism for smaller (< 0.3 μm) aerosols. An equation for the overall collection efficiency in a fixed bed was derived:

$$\ell n \left(\frac{N_o}{N}\right) = \frac{3\eta\alpha H}{2d_c} \qquad (7)$$

where $N_o$ = inlet particle concentration,

$N$ = outlet particle concentration,

$\eta$ = target efficiency per bed granule, % (a composite of several contributions)

$\alpha$ = solids fraction in bed

$H$ = bed height, cm.

While single particle efficiencies are rather low, the number of aerosol-granule interactions is very large as the gas stream passes through the bed. Single-stage fluid beds exhibit somewhat lower collection efficiencies than comparable fixed beds due to the bypassing of some collection mechanisms by the gas bubbles created during fluidization. This effect also accounts for the fact that multi-stage fluid beds are more effective than a single bed of the same overall height, because in the latter the growth of bubbles by coalescence reduces the efficiency. Assuming complete mixing between stages and a constant stage efficiency, collection by n beds in series would result in; an overall collection efficiency of

$$E = \frac{100(N_o - N)}{N_o} = 100\left[1-(1-E')^n\right] \qquad (8)$$

where $E$ = overall collection efficiency, %

$E'$ = fractional collection efficiency per stage.

The lower collection efficiency of a fluid bed compared to a fixed bed can thus be offset by staging, and the ease of solids handling/recirculation feature of a fluid bed is a definite operating advantage.

Peters _et al_. (23) have developed a mathematical model simulating aerosol removal in a fluid bed based on bubble assemblage concepts and particulate collection mechanisms. Model predictions were shown to compare favorably with experimental results and the model allowed a quantification of the effect of gas bypassing on overall bed efficiency.

# EXPERIMENTAL

## Equipment

The experimental apparatus used in this study, shown schematically in Figure 2 and listed in Table 1, can be roughly divided into three major categories: 1) the combustion system, 2) the gas handling system including the fluid bed, and 3) the instrumentation. Figures 3, 4, and 5 are photographs which collectively show all of the actual equipment plus the graduate and undergraduate students who assisted in the work. The combustion system consisted of a diesel fuel supply tank, a modified Model 55JZ-4C-5 3/4 International Heater Co. domestic furnace oil burner (with fuel pump/combustion air blower, high voltage spark igniter, and 0.85 gallons/hr fuel orifice/nozzle), a refractory lined "fire box" combustion chamber adapted from another home furnace, and a section of triple-walled chimney pipe. The gas handling system consisted of the various pieces of single wall steel chimney pipe/duct work (12.7 cm (5 in) I. D. upstream of main blower, 25.4 cm (10 in) I. D. downstream of main blower); a flue gas damper, a sliding panel augmentation air intake control mounted concentrically around the hot gas intake line at the suction of the main air blower (Dayton Model 4C108, 1HP, 3450 RPM, direct drive); the fluid bed zone fashioned from 25.4 cm I. D. chimney pipe sections with a 100 mesh stainless steel wire screen distributor supported both above and below by a coarse wire screen attached by bolted flanges to the chimney pipe and sealed with rubber gaskets, silicone and epoxy sealants, and high temperature duct tape; and a similarly sealed, flanged orifice plate for flow measurement downstream of the bed. The fluid bed zone was fitted with three opposing pairs of glass windows: one pair for viewing internal bed behavior, and one pair each for transmitting and detecting the light used for in situ opacity determination. Pressure taps drilled above and below the bed were used for both pressure drop measurements and gas sampling.

The instrumentation used in the study consisted of: a Setra Systems Model 239E electronic differential pressure transducer and associated chart recorder and/or Fluke volt/ohm-meter used for recording pressure drop across the orifice (for gas flow rate determination); a draft gauge/manometer for bed pressure drop measurements; five iron-constantan thermocouples and associated six channel Analog Devices Model AD 2036 digital thermometer for measurement of bed inlet gas, bed, bed outlet gas, orifice inlet gas, and orifice outlet gas temperatures; and two photocell light detectors with separate light sources. Each photocell was wired, encased in an aluminum support, and mounted on a detachable steel band encircling the fluid bed zone. Each light source was wired to a 5 volt regulated power supply and mounted in the same manner as the corresonding photocell. These source/detector pairs were positioned outside windows on either side of the bed zone above and below the bed. Shrouding of the detectors with metal foil prevented intrusion of stray light. The voltage output of the photocells varied dramatically with transmitted (incident) light intensity and thus provided a good measure of gas opacity. The output signals from the photocell detectors were simultaneously recorded on a two pen, multi-range input, Houston Model B-5000 strip chart recorder and periodically confirmed using a millivoltmeter. Either an Anderson Model 2000 Stack Gas Sampler (Impactor) or a filter housing containing Whatman No. 1 filter paper was used in conjuction with a downstream vacuum pump and rotameter for smoke particulate size distribution/total concentration determination for gas samples.

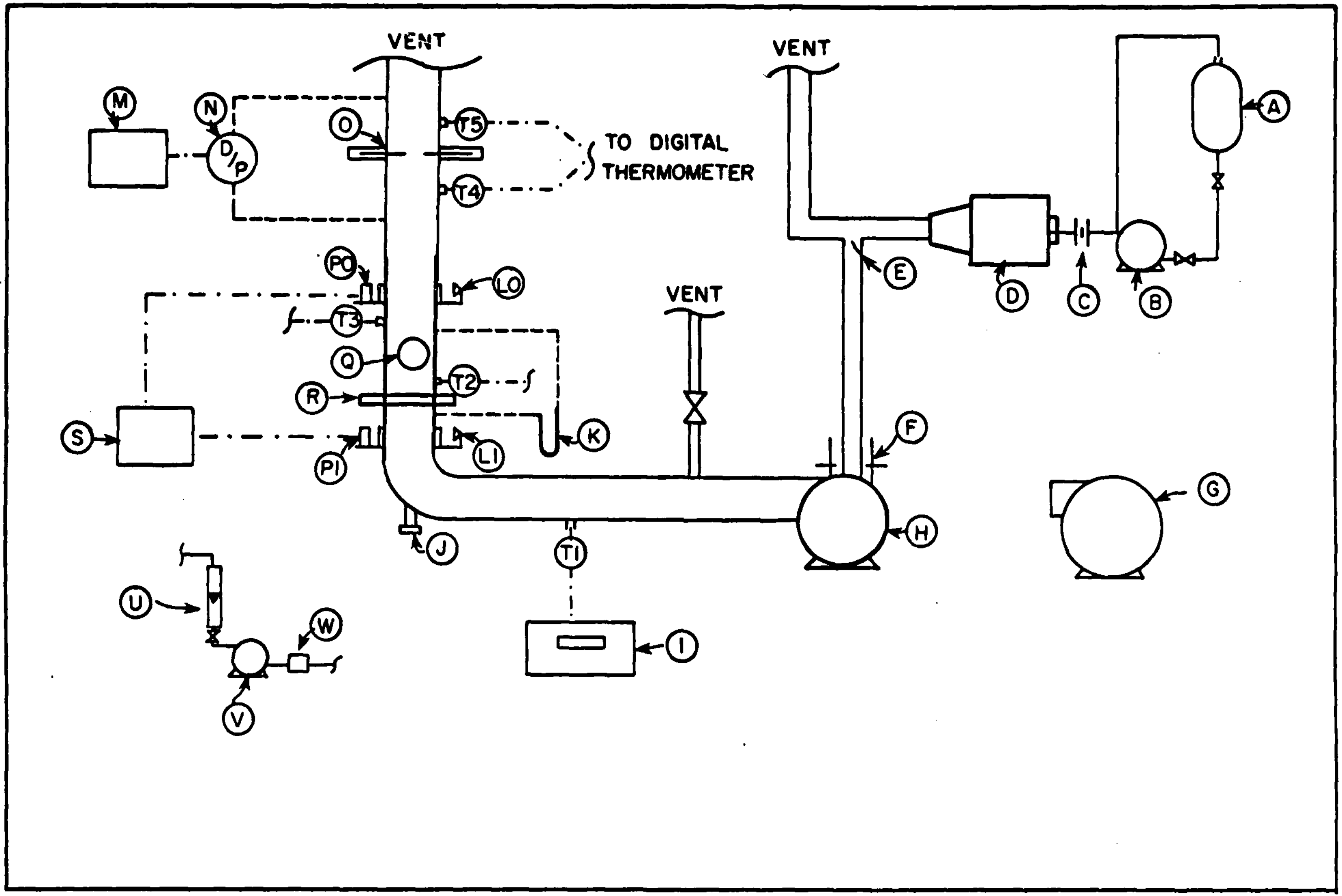


Figure 2. Schematic Diagram of the Experimental Apparatus

TABLE 1. LEGEND FOR SCHEMATIC DIAGRAM (Figure 2)

| SYMBOL | DESCRIPTION |
|---|---|
| A | Diesel fuel feed tank |
| B | Fuel pump/air blower for furnace |
| C | Fuel nozzle |
| D | Furnace burner with igniter, etc. |
| E | Flue gas damper |
| F | Sliding panel augmentation air intake control, concentric with smoke intake on main blower |
| G | Supplemental air blower for cooling of main blower motor |
| H | Main blower |
| I | Digital thermometer |
| J | Soot purge pipe for periodic distributor cleaning via "blow-back" |
| K | Water manometer for measuring bed pressure drop |
| LI | Power-regulated light source for bed inlet opacity detector |
| LO | Power-regulated light source for bed outlet opacity detector |
| M | Two pen chart recorder for orifice pressure drop measurement |
| N | Electronic differential pressure transducer for orifice $\Delta P$ |
| O | Flanged plate with 5 cm hole (orifice) for gas flow determination |
| PI | Photocell/detector for inlet smoke opacity measurement |
| PO | Photocell/detector for outlet smoke opacity measurement |
| Q | Viewing ports/windows (two 180° apart) for fluid bed |
| R | Fluid bed distributor (flanged screen) |
| S | Two pen chart recorder for photocell/detector output |
| T1 | Bed inlet gas thermocouple |
| T2 | Bed thermocouple |
| T3 | Bed outlet gas thermocouple |
| T4 | Orifice inlet thermocouple |

TABLE 1 (continued)

| SYMBOL | DESCRIPTION |
|---|---|
| T5 | Orifice outlet thermocouple |
| U | Gas sampling rotameter |
| V | Vacuum pump for gas sampling |
| W | Filter housing or impactor for gas sampling |

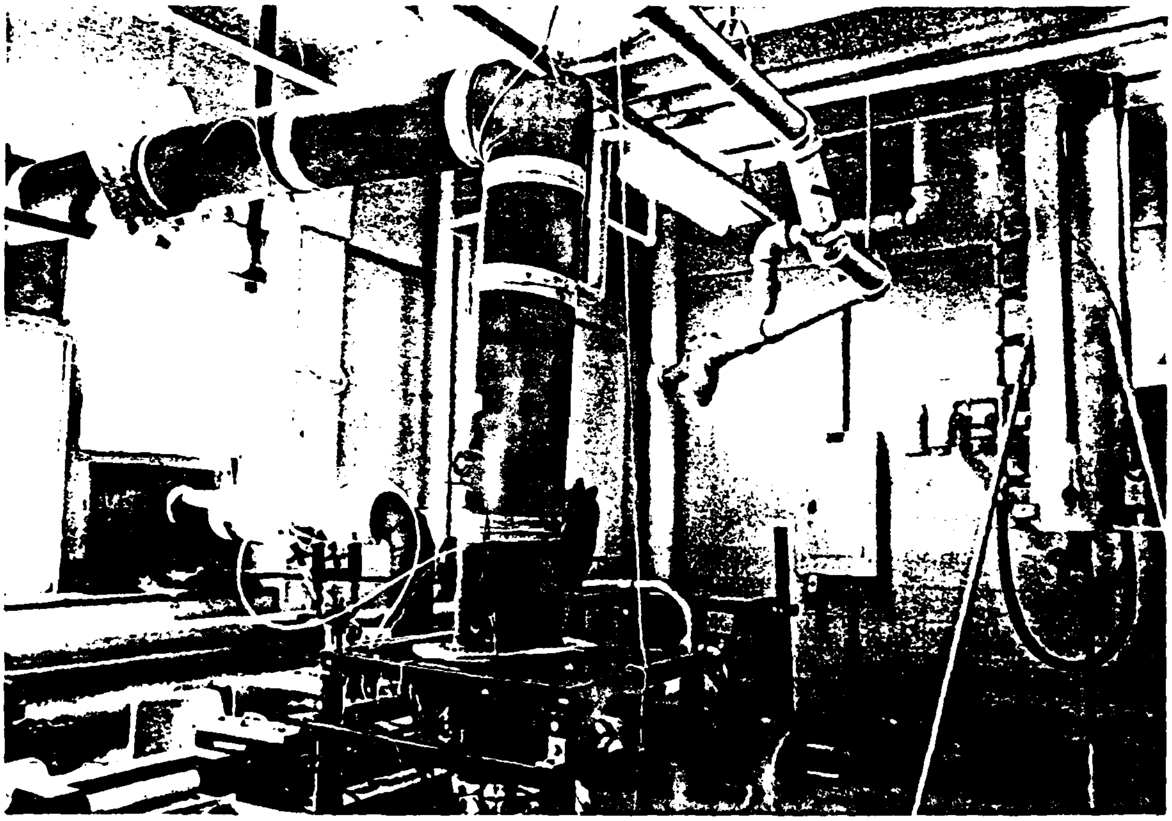

Figure 3. Photograph of Entire Apparatus

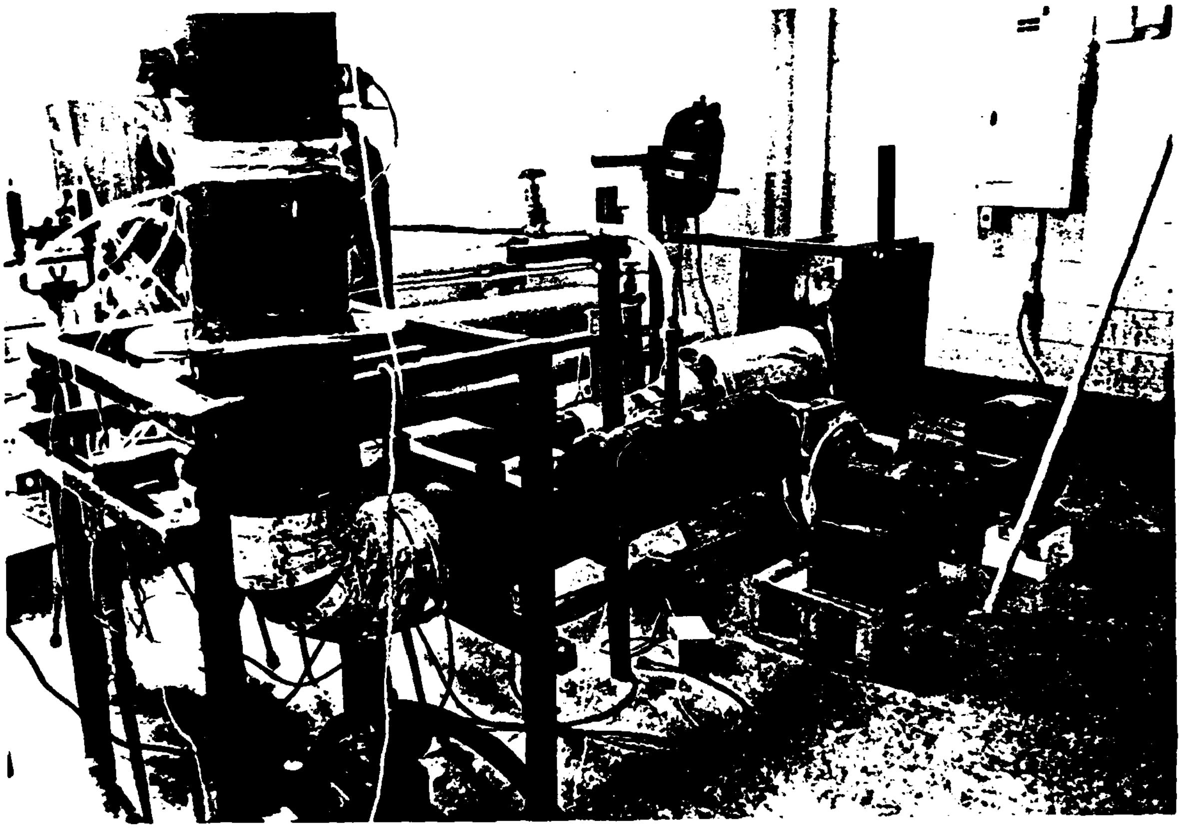

Figure 4. Close-up Photograph of Fluid Bed Section

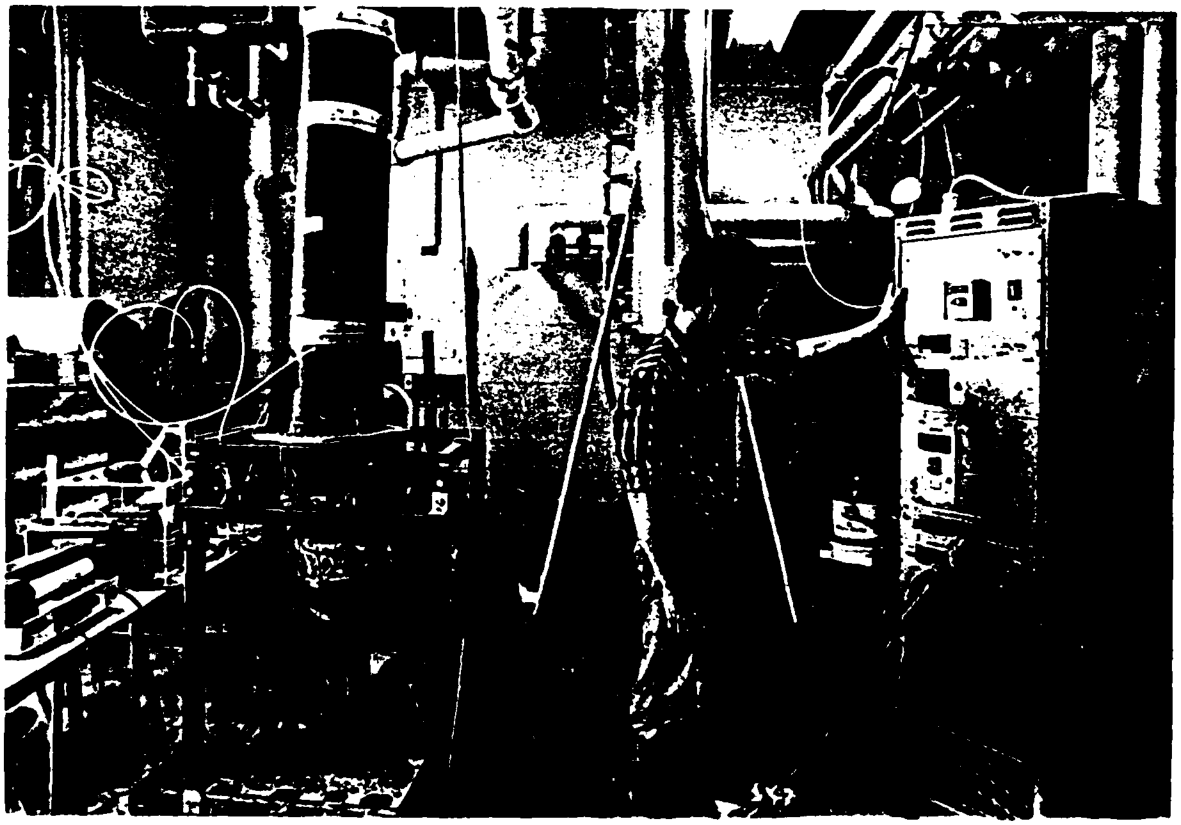

Figure 5, Photograph Showing Instrumentation

## Materials

The principal materials involved in this study were the conventional diesel fuel used in the burner and the glass microspheres used in the fluid bed as the "filter medium." These glass beads, with a particle density of 2.5 g/ml, were obtained from the Cataphote Division of Ferro Corp. Beads were close-sieved to two different volume-average diameters of 506 µm and 1090 µm, or, nominally, 500 and 1100 µm, respectively.

## Preliminary Equipment Testing

Before describing the detailed procedure used in a typical experiment, mention should be made of some preliminary steps taken in the study. The air handling system previously described as being used in the study was not the first configuration tested. After nearly three months of acquiring and assembling the various major components, it was found that the original configuration was impractical. At that time the entire exhaust from the furnace was routed into a Y-junction at a venturi-type section of the air duct downstream from the main air blower. It was hoped that the high fresh air flow would aspirate the smoke into the bed inlet piping and, indeed, this was the case when no glass beads were present. However, the added pressure drop of even shallow beds of glass beads was apparently enough to reduce blower output to a point where "blow-back" of smoke out of the furnace inlet frequently occurred. After numerous small modifications failed to correct the problem it was decided that the aspiration approach must be abandoned in favor of a major redesign in which only a portion of the hot furnace gas was mixed with augmentation air upstream of the main blower rather than downstream. Formerly it had been feared that the blower might malfunction at high temperature. To help guard against overheating, a secondary blower was used to blow room air over the main blower motor and housing. The system then worked satisfactorily, but the sensitivity of the main blower's volumetric output to downstream pressure drop, and thus bed depth, made it nearly impossible to independently set gas flow rate for a given bed depth. A small measure of flow control was achieved by the use of: 1) another vent line between the blower and bed, 2) the flue gas damper, and 3) the sliding panel control for air at the main blower intake. The latter two devices plus the crude air/fuel control on the oil burner allowed some variation of the smoke concentration seen by the fluid bed filter. Keeping the system sealed to prevent smoke escape into the laboratory required frequent re-applications of heat resistant caulking and tape.

Various calibration had to be performed prior to, and in some cases, in between, the filtration runs. The use of the orifice/differential pressure transducer required prior calibration of flow rate versus pressure drop, i.e., determination of the orifice coefficient as a function of gas velocity. This was accomplished using an anemometer. In order to be able to calculate percent opacity reduction (POR) in the filtration studies, it was necessary to relate the results obtained from the inlet photocell/light source pair with those for the outlet. This involved extensive "cross-calibration" of the two devices by recording detector output when each of five calibration standards, which in this case, were wire screens of different mesh size, were placed perpendicular to the light path. The minimum fluidization velocity, $u_{mf}$, for each of the two bead sizes used was determined in the conventional manner (7) and found to be 16 cm/s and 50 cm/s for the 500 and 1100 µm beads, respectively; roughly in line with existing correlations (7).

Procedure

The procedure for a typical filtration run will now be summarized. The first step was to open the system at a piping junction above the bed zone, lift the outlet piping section using a rope hoist, clean the interior window surfaces and distributor of previously accumulated soot, fill the bed zone with clean beads to the desired bed depth, lower the outlet piping, re-seal the system, and level the distributor. Next, electric power was turned on and the instruments were allowed to warm up for 15 minutes after which the inlet and outlet smoke detectors were cross-calibrated as described in the preceding section. The fuel tank was filled with at least two gallons of diesel fuel, the two fuel inlet valves were opened, the flue gas damper was closed, and the furnace burner switches for fuel pump/blower and ignition were turned on. The furnace was allowed to run for 30 minutes, during which time the entire exhaust exited from the building via the furnace vent piping shown in Figure 2. Chart recorders for opacity readings, orifice pressure drop (or temperature) were turned on to establish baseline (reference) readings and initial temperature and bed pressure drop readings were manually taken.

Next, the sliding panel augmentation air control was set, both the supplemental and main air blowers were started up, and the flue gas damper was partially opened to introduce smoke into the main blower suction. With smoke now reaching the fluid bed filter, the run time, various temperatures and pressure drops, plus the detector (opacity) readings were either automatically or manually recorded at frequent intervals for the desired run length. As shown in Figure 6 the system reached relatively constant temperature within 15-20 minutes after the blower was turned on. Typically, after 50-75 minutes on stream the burner was cut off and the system was allowed to purge and cool with the main blower still on. This was generally accomplished in 20-30 minutes, after which the blowers were turned off, the final detector output was noted (to be used later in correcting for "baseline drift" caused by gradual soot accumulation on the windows), and the instrumentation, etc., turned off. Finally, the bed zone was opened, as previously described, and the now-dirty beads were vacuumed into a bag using a conventional heavy duty vacuum cleaner. These beads were subsequently cleaned manually using an agitated soap and water solution followed by decanting of liquid and overnight oven drying.

Gas sampling was performed during several of the later runs in order to obtain estimates of inlet and outlet soot particle size distribution using the Andersen impactor or total particulate loading using a cartridge containing filter paper. In either case, the gas was ampled from the system at a flow rate of roughly 6 std. ℓ/min (0.2 SCFM) which was slightly higher than the isokinetic rate. To accomplish this, a piece of 0.6 cm (0.25 in) noninal O. D. copper tubing was bent into a 90° bend and attached via tube fittings to the inner and outer walls of the bed zone through a pressure tap. The tubing bend was pointed downward and centered radially in the bed zone. The gas was withdrawn over a sampling period of 5 minutes, passing in succession through the tubing, impactor or filter cartridge, vacuum pump, and rotameter.

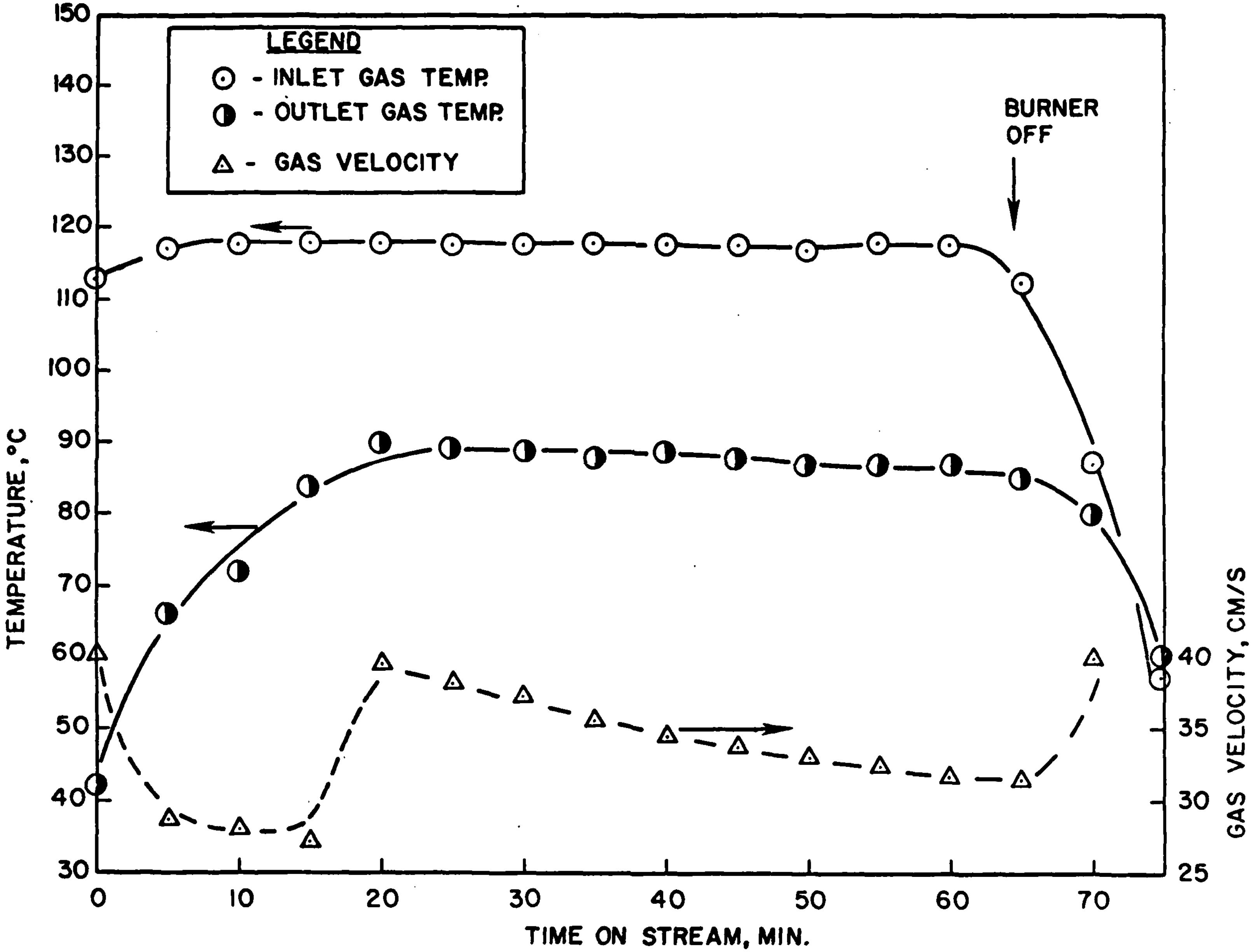


Figure 6. Plot of Temperature and Gas Velocity versus Time, Run 6

# RESULTS

## Opacity Reduction Studies

Once the system had been assembled and made workable, a total of 16 separate filtration runs were performed. Of these, 10 are considered relevant for this report, the other 6 being omitted because either equipment malfunctions or human error raised doubts about the validity of the data. Of the 10 runs reported here half involved 500 μm beads and the other half involved 1100 μm beads. Bed depths studied ranged from 2.5 cm to 10 cm (1 to 4 in). Bead size and bed depth were the two main "controlled" variables. However, because the single speed blower's gas output was extremely sensitive to bed depth, the gas velocity was closely coupled to bed depth, and thus was a variable although not an independent one. Table 2 provides a summary of average run conditions and other data for each run. Note in Table 2 that the pressure drop across a given bed was roughly equal in cm $H_2O$ to the bed depth. Table 3 concisely presents the most important results of the study, namely the percent opacity reduction (POR) range and average value for each run. The variation of POR with time is shown for the 500 μm bead runs in Figure 7 and for the 1100 μm bead runs in Figure 8. The variation of POR with bed depth and superficial gas velocity is summarized in Figures 9 and 10, respectively. Note that POR values ranged from 40% to nearly 100%.

The principal index of filtration efficiency used here, POR, is defined as follows

$$POR \quad \frac{OPD_{in} - OPD_{out}}{OPD_{in}} \times 100\% \qquad (9)$$

where POR = percent opacity reduction, %

$OPD_{in}$ = "corrected optical density" of the bed inlet gas, measured as voltage (photocell output signal)

$OPD_{out}$ = "corrected optical density" of the bed outlet gas.

The term "corrected" implies that the values were 1) corrected for baseline drift due to soot deposition on the windows, 2) corrected for variation of photocell output with detector temperature (where appropriate), and 3) put on a common basis by using the cross-calibration results for the two different photocells. With these various corrections, the POR values are a direct measure of the extent of smoke visibility (opacity) reduction accomplished by the bed of glass beads, since early runs demonstrated that the wire screen distributor accomplished virtually no filtration.

## Supplemental Measurements

Attempts to measure the percentage reduction in smoke particle loading (concentration) were only partially successful because of the difficulty in obtaining reproducible (or even believable) weight changes for the filter paper/deposited soot samples. In many cases, after passing, e.g., 28 std. ℓ (1 $ft^3$) of gas through filter paper and observing a distinctly black deposit of soot, a <u>negative</u> weight change was found, making the results meaningless. Various techniques were tried in order to minimize such problems, e.g., either pre-wetting,

TABLE 2. SUMMARIZED RUN DATA

| Run No. | Date 1984) | Run Length min | Nom. Ave. Bead Dia. $d_c$ μm | Bed Depth D cm | Average Temperatures Bed Inlet $T_{in}$ °C | Bed Outlet $T_{out}$ °C | Bed Average $T_B$ °C | Average Bed Pressure Drop $\Delta P_B$ Pa(in $H_2O$) | Average Superficial Gas Veloc. u cm/s | Avg. Gas Flow Rate v SLPM(SCFM) | Bed Condition |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 7/25 | 70 | 1100 | 2.5 | 101 | 85 | 93 | 516(2.1) | 60 | 1416(50) | Fluid (spouting) |
| 6 | 6/20 | 70 | 1100 | 5.0 | 118 | 87 | 102 | 688(2.8) | 35 | 850(30) | Marginally Fluid |
| 16 | 8/9 | 55/30* | 1100 | 5.0 | 81/76 | 68/63 | 75/70 | NM | 44/37 | 1105/906 (39/32) | Marginally Fluid |
| 4 | 6/14 | 70 | 1100 | 7.5 | 122 | 80 | 101 | 959 (3.9) | 6.4 | 159(5.6) | Fixed |
| 14 | 8/3 | 100 | 1100 | 7.5 | 95 | 75 | 85 | NM | 6.1 | 150(5.3) | Fixed |
| 11 | 6/27 | 70 | 500 | 5.0 | 163 | 133 | 148 | 664(2.7) | 40 | 991(35) | Fluid (spouting) |
| 9 | 6/22 | 65 | 500 | 7.5 | 105 | 84 | 95 | 885(3.6) | 9.5 | 232(8.2) | Marginally Fluid |
| 15 | 8/8 | 75 | 500 | 7.5 | 90 | 75 | 82 | NM | 37 | 906(32) | Fluid |
| 5 | 6/19 | 55 | 500 | 10.0 | 123 | 52 | 88 | 1008(4.1) | 1.8 | 45(1.6) | Fixed |
| 13 | 7/27 | 65 | 500 | 10.0 | 119 | 45 | 82 | NM | 1.8 | 48(1.7) | Fixed |

* Run was intentionally interrupted for a 45 minute cool-down period followed by re-start.

TABLE 3. SUMMARIZED RESULTS FOR FILTRATION RUNS

| Run No. | Nominal Avg. Bead Diam. $d_c$ µm | Bed Depth D cm | Percentage Opacity Reduction POR % | |
|---|---|---|---|---|
| | | | Range | Average |
| 12 | 1100 | 2.5 | 37-57 | 49 |
| 6 | 1100 | 5.0 | 66-96 | 75 |
| 16 | 1100 | 5.0 | 73-85 | 79 |
| | | | | Avg=77 |
| 4 | 1100 | 7.5 | 89-98 | 93 |
| 14 | 1100 | 7.5 | 82-96 | 92 |
| | | | | Avg=92 |
| 11 | 500 | 5.0 | 51-76 | 63 |
| 9 | 500 | 7.5 | 62-94 | 86 |
| 15 | 500 | 7.5 | 77-89 | 84 |
| | | | | Avg=85 |
| 5 | 500 | 10.0 | 99-100$^-$ | 99$^+$ |
| 13 | 500 | 10.0 | 96-100$^-$ | 98$^+$ |
| | | | | Avg=99 |

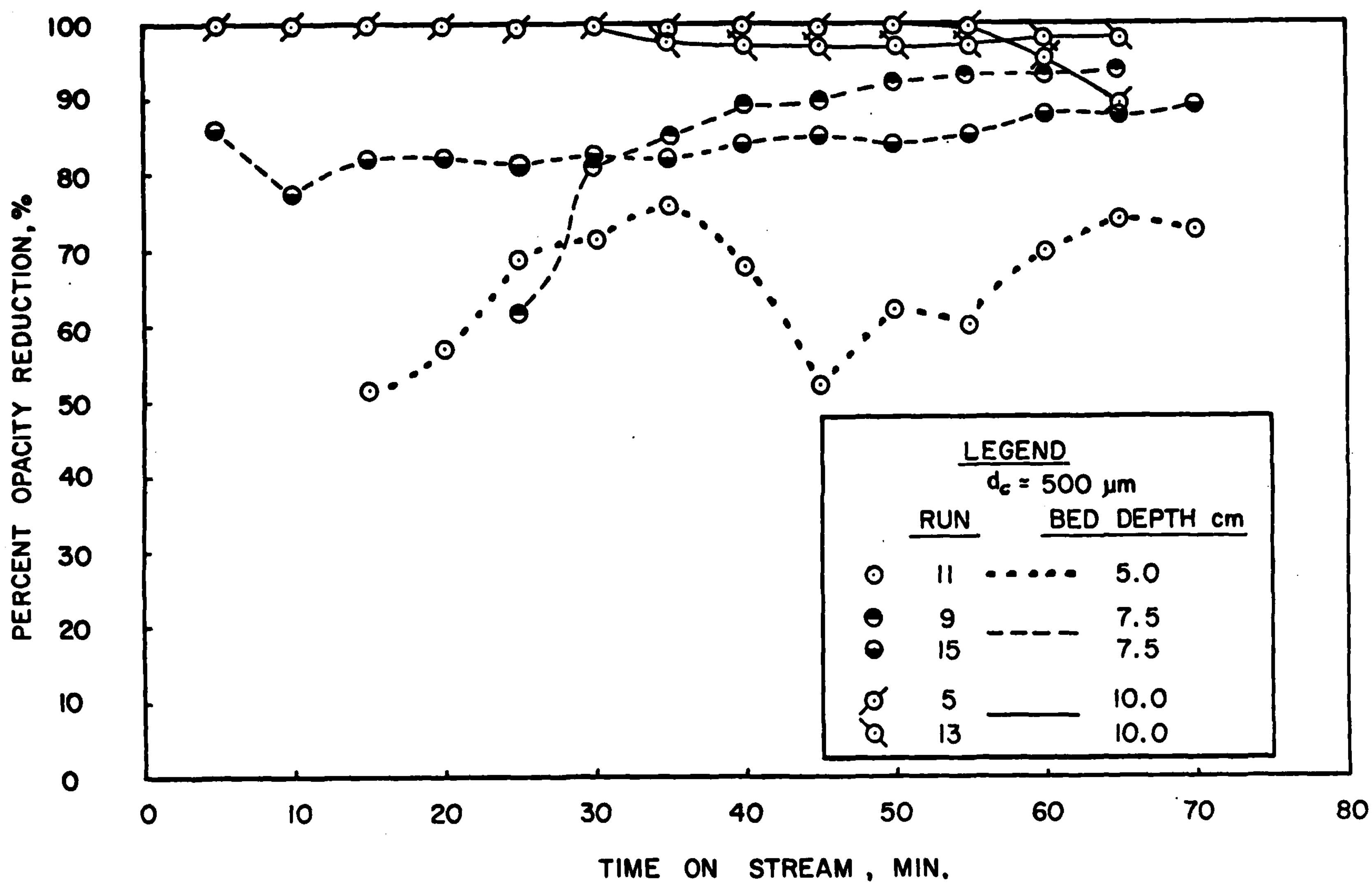


Figure 7. Percent Opacity Reduction versus Time Results for 500 μm Bead Runs

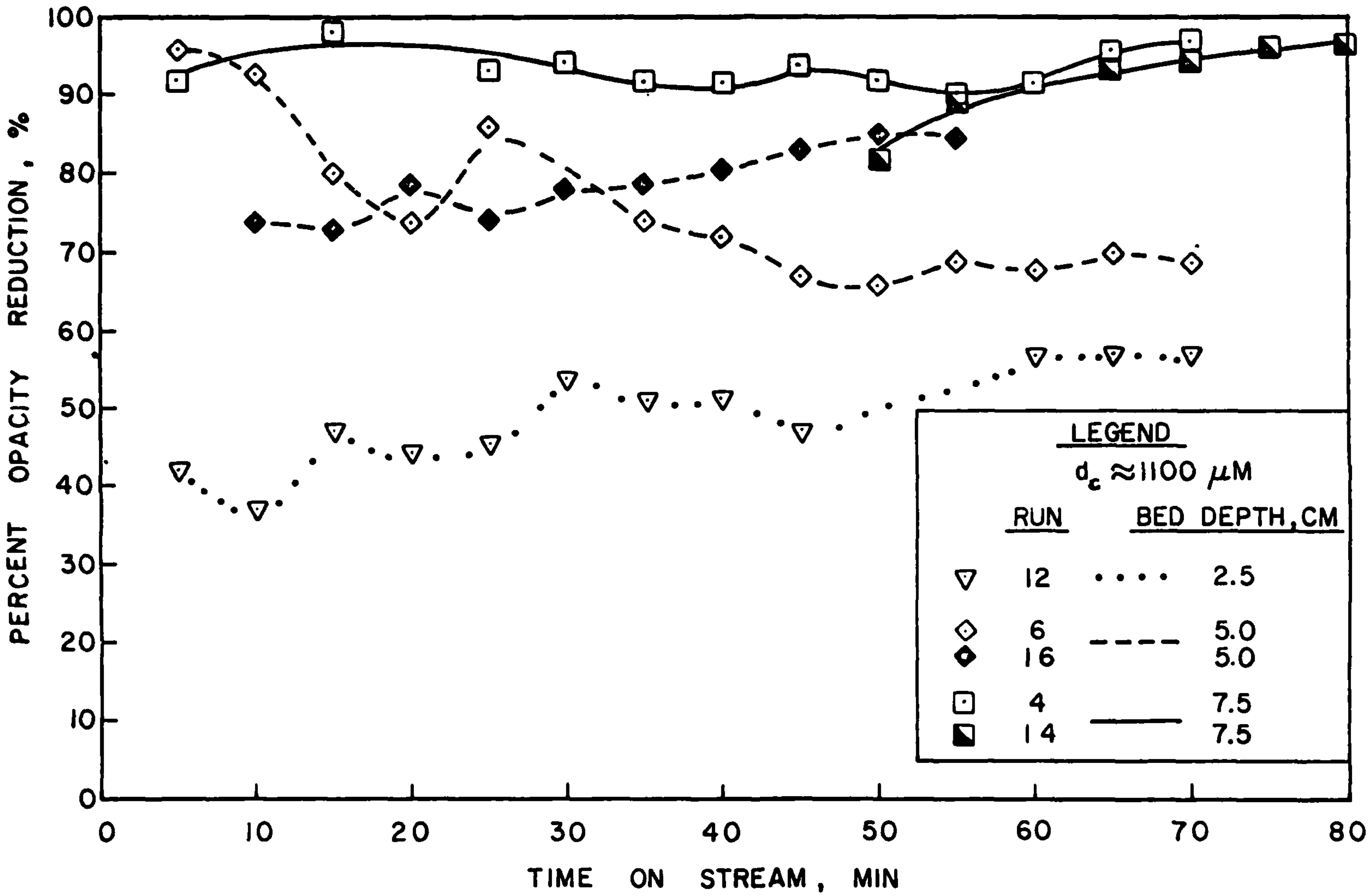


Figure 8. Percent Opacity Reduction versus Time Results for 1100 μm Bead Runs

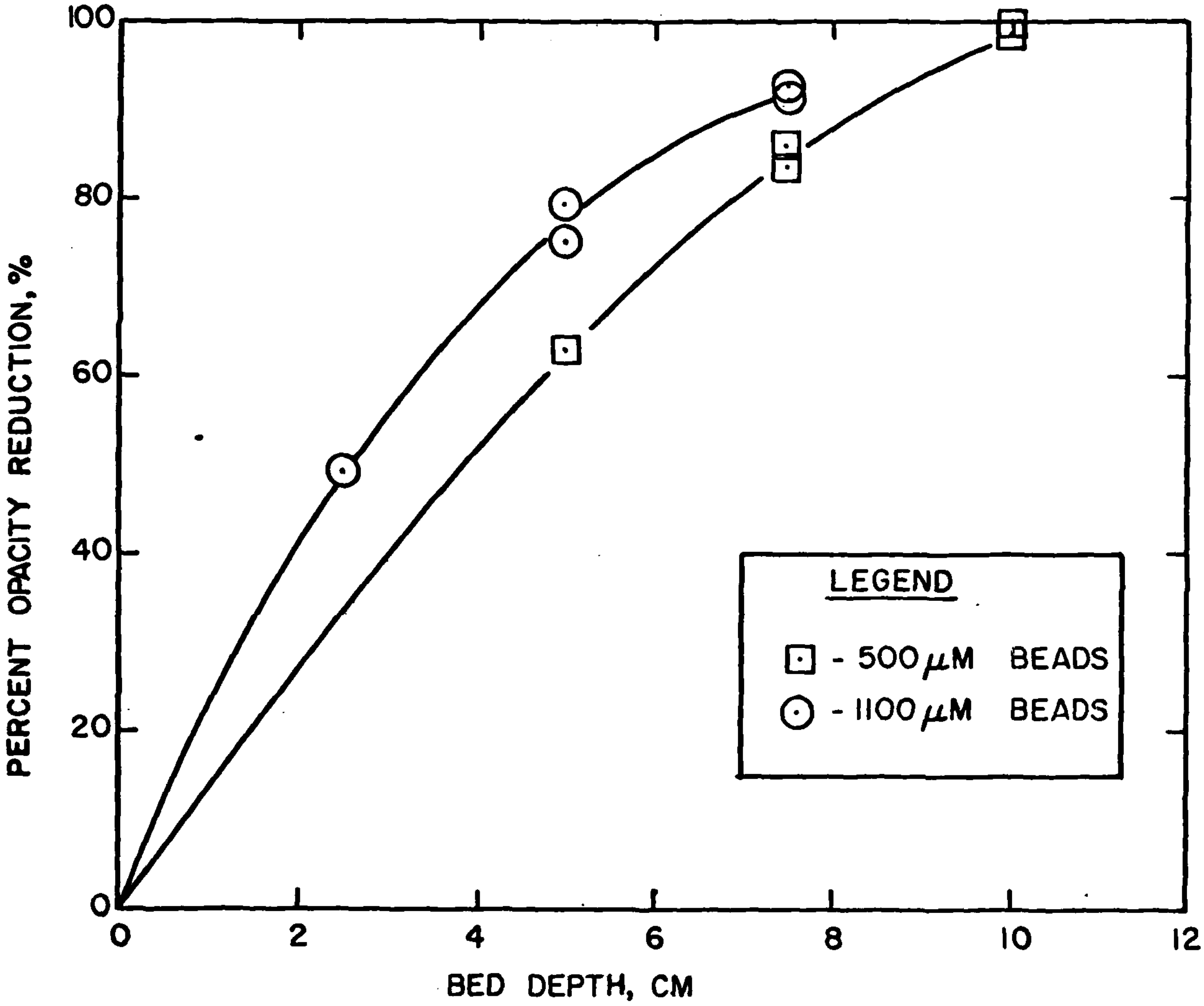


Figure 9. Percent Opacity Reduction as a Function of Bed Depth

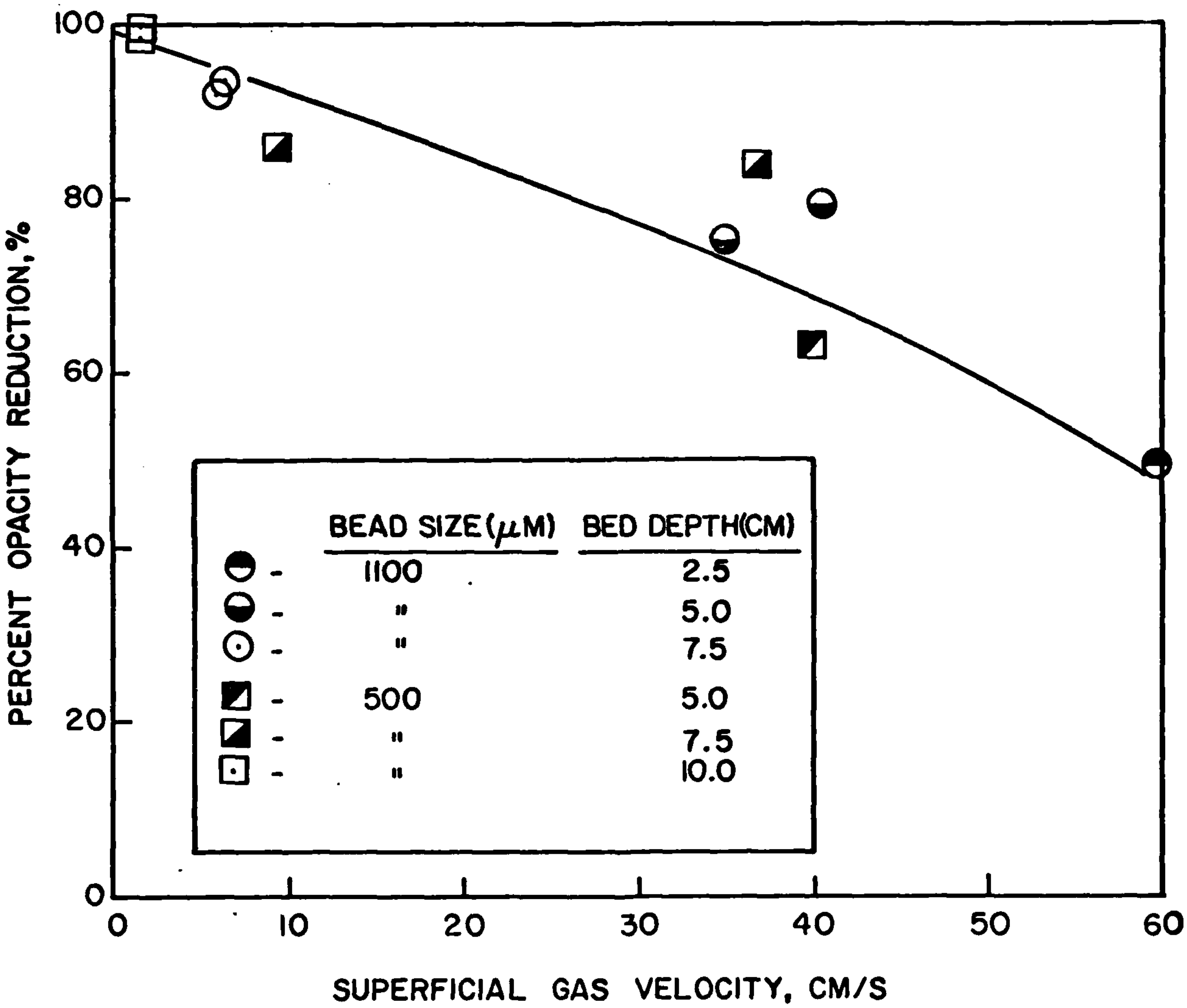


Figure 10. Percent Opacity Reduction as a Function of Superficial Gas Velocity in the Bed

pre-drying, post-drying the paper, the use of standards, etc., and some helped. However, the fundamental problem is that such determinations of amount of (deposited) soot in a given volume of gas fit the classic problem of obtaining accuracy in a measurement of the very small value difference between two separately determined and much larger quantities. The moisture picked up from or lost to the atmosphere by the filter paper was often greater than the weight of deposited soot. The only solution appeared to be to take a large number of samples for each measurement and average them statistically, but the time involved was felt to be prohibitive considering the value gained. Accordingly, in some instances, an estimate of relative concentration (used in estimating percent mass filtration and particle size distribution) was obtained by visual examination of the filter paper or impactor stages. An optical microscope was helpful in this approach. Although only semi-quantitative, such filtration results were in reasonable agreement with POR data and the particle size distribution results were roughly in line with typical values for diesel-derived soot.

Measurements of soot concentration were made and the inlet gas values from various runs ranged from $1 \times 10^{-5}$ to $1 \times 10^{-4}$ g/std. ℓ ($3 \times 10^{-4}$ to $3 \times 10^{-3}$ g/SCF), averaging about $3.5 \times 10^{-5}$ g/std. ℓ ($1 \times 10^{-3}$ g/SCF). Rough estimates of the inlet gas soot particle size distribution obtained from impactor data for Run 14 are presented in Table 4. Although not shown, a virtually indistinguishable soot size distribution was found for the bed outlet gas in this case (at POR ≈ 70%).

Filter paper weight change/visual estimation results for soot concentration during Runs 15 and 16 indicated 70% and 90% mass filtration when the opacity reduction (POR) values were 75 to 80% and 85-90%, respectively.

TABLE 4. SOOT PARTICLE SIZE DISTRIBUTION DATA

| Soot Particle Diameter* $d_p$ μm | Estimated Mass Percent** $x_m$ mass % |
|---|---|
| >4 | <3 |
| 2.1 - 4.0 | 2 |
| 1.3 - 2.1 | 2 |
| 0.9 - 1.3 | 3 |
| < 0.9 | >90 |

* Determined using eight stage Andersen Model 2000 Stack Gas Sampler (Inertial Impactor) at a gas flow of 6 std ℓ/min (0.2 SCFM); Inlet gas sample from Run 14

** Combined gravimetric/optical estimation method

DISUCSSION

The primary objectives of this study were 1) to demonstrate that fluid bed filtration can be effective as a means of removing aerosol soot from hot combustion gas exhaust and 2) to obtain a preliminary determinatin of the effect of several parameters, i. e., bed (collector) particle size, bed depth, and gas velocity, on filtraiton efficiency; or more specifically in this case, percent opacity reduction. It is felt that both of these objectives were accomplished.

Before discussing the results of the project, some additional mention should be made of several experimental difficulties encountered and overcome in the carrying out of this project, because they serve to illustrate that this was not as simple an experiment as it might first appear. Furthermore, the time expended in solving these problems somewhat shortened the ultimately fruitful protion of the grant period such that some facets of the topic which it had been hoped could be investigated, e. g., staged beds, independent control of gas velocity and soot concentration, more accurate soot particle size determination, etc., could not be fully explored and must await additional funding. One problem already cited was the single speed nature of the main air blower and its relatively low output at static heads exceeding, say, 10 cm (4 in) of water. This restricted experimentation to single stage, relatively shallow beds if fluidization was to be achieved. Indeed for the 7.5 cm deep, 1100 μm bead beds and 10 cm deep, 500 μm bead beds the bed was fixed, not fluid. The low developed head of the blower, particularly at high temperature, also made using a distributor with an appreciable, e. g., 2 cm $H_2O$, pressure drop impractical; yet such would have given a better gas distribution through the bed and would have made less frequent the incidence of "spouting" (localized violent bubbling due to preferential flow in a small region). In addition, there was the problem of lack of independent control of gas velocity which was only partially overcome by the adjustable intake flow restrictions on the blower's suction. A very formidable problem concerning the photocell detectors used in the early runs was later solved, but forced re-doing of these runs. The first photocells used were found to be extremely temperature sensitive, thus the gradual warming of the detector due to its proximity to the hot bed zone caused dramatically misleading output signals for temperature changes as small as 5°C. The use of new, temperature-insensitive photocells (working on a different principle) eventually solved this problem and some of the early data were salvaged by factoring out the temperature-induced detector drift.

It had been hoped that relative soot concentration measurements could be made using a Unico Model 80 TS Tape Sampler/Dust Densitometer and used as a supplement to the photocell measurements. However, early attempts to do so revealed that the soot levels were much too high for practical use of this device.

Turning to the filtration results, it bears repeating that the percent opacity reduction values were found to correspond reasonably closely with the percent mass filtration values found, thus POR is a reliable index of filter efficiency. An important feature to note from Figures 7 and 8 is that, over the roughly 1 hour of each run, POR was relatively constant, appeared to decline with time in only one case (Run 6), and seemingly increased slightly in several cases. It would appear that, even for the shallow beds which accumulated the greatest overall amount of soot (due to much higher gas flow), the filter bed was far from "collected soot saturation" after periods of up to 1.5 hours. The implication of this is that such a system, if employed for test cell exhaust filtration, would require only modest rates of collector particle (sand) removal and replacement when operated in the continuous mode and could possibly be operated in a batch mode with periodic replacement of the entire bed. Before conducting this study it had been thought that filtration efficiency might fall off appreciably as the glass beads became coated with submicron sized soot. The various mechanisms believed to account for filtration in such a system were discussed in the Background section of this report and it seems likely that both interception and diffusion (Brownian) contributed here; but it is possible that small electric charges present on some of the soot aided "capture" by the collection beads by inducing a small attractive force. In any case, the formation of a concentric shell of soot on the beads did not retard collection in the time involved. The nature of the force(s) initially binding soot to the glass beads can only be speculated, but it may have included both weak induced Coulombic and van der Waals effects. A persistent worry before starting the project was the possibility that soot capture would be only momentary and that, after a short period of effectiveness, the bed would re-emit an appreciable fraction of the initially collected soot. The strong retention of the deposited soot was a very encouraging finding.

Figures 7 and 8, and more specifically, Figure 9, show that, as expected, POR increased with increasing bed depth. Figure 9 appears to indicate a significant advantage in POR for 1100 μm beads relative to 500 μm beads at a given bed depth, but this comparison is not straightforward becasue of the different gas velocities involved. Figure 10 shows a much less dramatic difference in the two when the comparison is made at constant gas velocity. Ideally the effect of bed depth could be studied in "isolation", i.e., at a fixed gas velocity, but this was not possible here for reasons already cited. Nevertheless, it is interesting to note that the increase in POR with bed depth for these single stage beds follows reasonably closely the pattern that would be expected for multi-staged beds. Equation 10 is a modified version of Equation 8 (Background section) in which POR and POR' have been substituted for E and E', respectively:

$$POR = 100\,(1-(1 - POR')^{n}) \tag{10}$$

where POR = overall percent opacity reduction, %

POR' = fractional opacity reduction per stage.

n = number of identical stages in series

Taking the 49% average POR (POR' = 0.49) value for the 2.5 cm deep bed of 1100μm beads and viewing a 5.0 cm bed of such beads as a pseudo two-stage bed (2.5 cm/stage) Equation 10 would predict a POR value of 74% for the 5.0 cm bed. The actual respective values found in Runs 6 and 16 were 75 and 79%, averaging 77%. Similarly for a 7.5 cm, 1100 μm bead bed, this approach would predict POR = 87% and the measured value (Runs 4 and 14) averaged 92%. Based on the 63% POR value for the 5.0 cm, 500 μm bead bed, this pseudo-staged bed calculation yields predicted POR values of 78 and 87% for the 7.5 and 10 cm beds, respectively. The corresponding actually measured values were 85% (Runs 9 and 15) and 99% (Runs 5 and 13). Ordinarily one would expect a single 10 cm deep bed to be slightly less efficient than two 5 cm deep beds in series, rather than more efficient as the results of this study indicate. However, two things must be remembered, namely, that Equation 10 is based on the implicit assumption that gas velocity is the same for all cases and also that the cases being compared are all for the same flow regime, i.e., fixed bed or fluid bed. In the actual cases gas velocity decreased with the increasing bed depth and the deepest beds (7.5 cm for 1100 μm beads, 10 cm for 500 μm beads) operated as fixed beds while the shallower beds were fluid. Both of these latter-mentioned considerations would tend to increase actual POR relative to the predictions of Equation 10, thus the data are relatively consistent.

Finally, a brief discussion will be given connecting this experimental study to potential application of fluid/fixed bed filtration for aircraft engine test cell exhaust. First, it should be noted that the average soot concentration ($1 \times 10^{-3}$ g/SCF = 0.02 grains/SCF) falls in the range of 0.01 to 0.08 grains/SCF commonly found for jet engine exhaust. The soot particle size distribution found here (> 90% less than 0.9 μm) is also similar to that associated with aircraft engine smoke. As indicated in Figure 1, the temperature of the water-quenched exit gas from a typical test cell might be expected to fall in the 150-400°F (66-204°C) range and the inlet gas to the filter bed in this study ranged in temperature frm 90 to 163°C. The gas velocities studied here are admittedly lower than would be used in a test cell fluid bed, but cover a wide enough range that extrapolation of the observed trends to higher velocity can be done with confidence. Based on a typical test cell exhaust flow rate of $8 \times 10^5$ ACFM (1, 2) the diameter of a cylindrical fluidized bed filter would need to be roughly 28 m (92 ft) if a superficial gas velocity of 60 cm/s (2 ft/s), the highest studied in this investigation, were to be used. It is much more reasonable to use, say 1100  m or larger sized sand or glass particles at 1.5 to 2.5 times the minimum fluidization velocity (bubbling bed mode). This would imply a typical gas velocity at the bed of 1.5 m/s (5 ft/s) which would require an 18 m (58 ft) diameter bed. Assuming a particle density for glass or sand of around 2.5 g/ml and a bed voidage of 0.5 this would correspond to approximately $3.1 \times 10^3$ kg (3.4 tons) of sand per cm of bed. A three-stage bed with each stage being 5 cm deep would probably be a reasonable compromise in terms of overall filtration efficiency and acceptable pressure drop.

## CONCLUSIONS

1. Fluidized bed filtration is a highly effective means of removing submicron aerosol soot particles from a hot gas stream, and, as such, deserves consideration as a practical, cost-effective way to significantly lower visible smoke levels for aircraft engine test cell exhaust.

2. Fixed single stage filter beds of 500-1100 µm collector particles (glass beads) with modest bed pressure drops (7.5 to 10.0 cm $H_2O$) were found to give 92-99+ % smoke opacity reduction in this study, but the gas velocities involved were (unavoidably) much lower than would be realistic for a practically-sized filter for a test cell. However, the shallow, single-stage (2.5 - 5.0 cm) fluid bed results (50-80% POR) at higher gas velocities do provide a basis for realistic assessment of this technology and these data imply that a multiple, e.q., 3,-stage fluid bed filter could achieve very high opacity reduction at relatively small overall pressure drops.

3. Smoke opacity reduction via fluid bed filtration appears to roughly follow a first order model with respect to bed depth, i.e., exponential decrease of opacity with increasing bed depth at a given gas velocity. The dependence of opacity reduction on gas velocity at fixed bed depth remains to be determined.

4. Adhesion of soot to bed (collector) particles is relatively strong and no decline in collection efficiency was observed over periods exceeding an hour on stream. This indicates that moderately "thick" (in relative terms) soot coatings can be tolerated before "sloughing off" or re-entrainment of previously deposited soot might be a problem.

5. No dramatic effect of soot particle size on filtration efficiency was detectable.

## RECOMMENDATIONS

1. The results of this study support the premise that fluid bed filtration has real potential as an economical means of significantly reducing aircraft test cell exhaust opacity, yet, because of the extremely limited budget and time involved, many important questions remain incompletely answered. Thus, if the U. S. Air Force remains interested in possible future application of this technology, it is recommended that further, more comprehensive, studies on the topic by this investigator or others be funded.

2. Further research on fluid bed filtration should explore the effect of the following factors on filtration efficiency: multi-staging of beds, gas velocity at constant bed depth and vice versa. Furthermore, longer term runs should be made to determine the threshold accumulated (deposited) soot on collector particle level at which bed change-out (batch mode) or recycling (continuous mode) should be considered.

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# APPENDICES

## APPENDIX I - Personnel

A. Principal Investigator

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B. Graduate Research Assistant

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Non-thesis related work on the project from 2/84-6/84

C. Undergraduate Research Assistants

John E. McLaughlin (2/84-6/84)
James R. Hunter (5/84-8/84)

## APPENDIX II - Interactions with Air Force Personnel

During the carrying out of this research project the only interactions with Air Force personnel were of a non-technical nature; specifically, these interactions were telephone and letter communications with Dr. Julian Tishkoff and Lt. Douglas Constant of AFOSR, Bolling AFB, D. C., concerning no cost extensions of the grant period. Originally it had been thought that it might be necessary to request the loan of a transmissometer (similar to the light source/photocell used for opacity measurements) from Major J. T. Slankas, HQAFESC/RDVS, Tyndall AFB, Fla., but this did not become necessary.

## APPENDIX III - Publications from this work

At this time, no publications (other than this report) have resulted from this work and no oral presentations have been made.

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