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# THE FEASIBILITY OF CONTROLLING TURBINE ENGINE TEST CELL PARTICULATE EMISSIONS WITH A BAGHOUSE


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CIVIL AND ENVIRONMENTAL ENGINEERING DEVELOPMENT OFFICE
(AIR FORCE SYSTEMS COMMAND)
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**20. ABSTRACT (Continue on reverse side if necessary and identify by block number)**

Air pollution regulations dictate that the Department of Defense attempt to control visible emissions emitted from turbine engine test cells. Previous studies have summarily dismissed baghouses as a control device because of potential size, pressure drop, explosion and fire hazard, and excessive cost. This report addresses these problems in the design of a baghouse for controlling emissions from a TF30-P100 engine.

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The results of the analysis indicate that it is possible to control test cellemissions with fabric filters and that this technique is cost competitive with the packed bed scrubbers currently used by the US Navy. Fiber filters are concluded to be preferable to scrubbers in cases of limited water supply and competitive in other cases.

PREFACE

This final report was prepared by Det 1 ADTC Civil and Environmental Engineering Development Office (CEEDO), Tyndall AFB, Florida. This work was accomplished under JON 21037A29. Major Peter S. Daley, Det 1 (CEEDO) ADTC was the project officer.

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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# EXECUTIVE SUMMARY

The use of baghouses (fabric filters) to control particulate emissions from turbine engine test cell facilities has in the past been considered infeasible. This report demonstrates that past studies have failed to adequately identify areas of uncertainty in this application. It has now been found that areas of concern such as baghouse size, explosion and fire hazards and excessive cost are not valid reasons to dismiss fabric filtration as a potential control technique.

The report includes the design of a baghouse for a TF30-P100 turbofan engine, the "worst case air handling problem". The design is specifically directed for use on Test Cell Number Four at Tinker AFB, Oklahoma.

The objective of this baghouse is to control visible emissions; therefore, the design specifications included a particulate control efficiency of 95 percent. The particle size distribution of the emissions was assumed to be approximately log normal with a mass median diameter of 0.1 μm and a geometric standard deviation of 10. The particle size distribution plotted on log-probability paper (Figures 3 and 4) demonstrates that compliance with a typical mass regulation of 0.1 lb of particulate per million Btu's of heat input can be achieved with only 17 percent control efficiency. However, compliance with visible emission regulations will require the 95 percent efficiency stated in the design specifications.

The competitive nature of the baghouse is demonstrated by a comparison with two other forms of emission control that have undergone prototype testing. These include wet electrostatic precipitators and packed bed scrubbers. The precipitator experienced problems with cleaning of the particulate collection plates and has not been fully evaluated at this time. The packed bed scrubber has just entered preliminary testing stages for two full-scale test cells.

A comparison of land requirements reveals that with cooling towers, water reservoir, recycle systems and solids treatment, approximately 6600 feet$^2$ will be required for the scrubber compared to the 8000 feet$^2$ for a baghouse. The maximum efficiency of the scrubber to date seems to be 85 percent with an average of 66 percent. The actual efficiency of a scrubber is deceiving since at least 50 percent of the collected particles are trapped in the augmenter itself, due to the spray rings, and not in the scrubber. Baghouse installations normally obtain efficiencies of 95 percent or greater. The scrubber has required up to 766 gpm of make-up water during a test, along with electricity to run the recirculation pumps, cooling towers and exhaust spray rings. The only water a baghouse may use would be in a spray ring to reduce gas volume (approximately 100 gpm for a maximum volume reduction of 10 percent). The low pollutant concentrations in a baghouse indicate that infrequent cleaning cycles will be required, hence, minimizing the amount of electricity required.

The scrubber requires a redesign of the augmenter tube whereas the baghouse does not. Cost projections for scrubbers have not included the expense of augmenter modifications.

A baghouse is well suited in this application for the following reasons:

(1) High efficiency

(2) Capability to filter out submicron particles

(3) Effectiveness when gas properties and process conditions vary

(4) Low energy requirements

(5) Capable of high temperatures (550$^{o}$F)

(6) Condensation on the bags is not a problem

(7) Concentrations of flammable compounds are below flammability limits

(8) Temperatures are below explosion temperatures

(9) Baghouse design can eliminate danger from sparks

(10) Amount of water required is low (or zero)

(11) Similar industrial applications exist providing experience

(12) Expected low pressure drop

(13) Additional noise abatement inherent in design

The final proposed design is outlined in Section VII of this report (including Figures 8 through 11).

PROPOSALS

(1) A pilot baghouse should be constructed to study cleanability and required frequency of cleaning.

(2) Loading on sample fabrics should be studied to determine caking characteristics, "blinding" problems and pressure drop.

(3) Development should be started on techniques of rapidly locating bag failures.

(4) Measurements of potential explosive compounds should be made and compared with lower explosive limits. This should include concentrations due to particulate buildup on the bags, during and between testing.

(5) Studies should be performed on the potential shock waves that could travel through the baghouse due to the engine fluctuations and startups. This study should include the potential use of these fluctuations as a cleaning mechanism.

(6) The slope required for the hopper walls should be determined by study of the particulate adhesion characteristics.

CONCLUSIONS

(1) It is feasible to control turbine engine test cell particulate emissions with baghouses under the conditions assumed in this report.

(2) The air flow volumes, at the conditions stated, are not excessive for control with a baghouse.

(3) Both excess and augmentation air sufficiently dilute the exhaust gas to temperatures permissible in baghouse operation.

(4) With the baghouse properly insulated, the temperature of the exhaust gas stream will remain above the dew point, thereby preventing condensation.

(5) The application of a baghouse to control particulate emissions is becoming more economical. In some respects ($/acfm and $/lb of particulate collected) a baghouse is currently less expensive than a packed bed scrubber.

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SECTION I

INTRODUCTION

1. BACKGROUND

Department of Defense and civilian airline turbine engine test facilities are under pressure to control visible emissions. Numerous studies have proposed various control techniques, such as wet electrostatic precipitators and scrubbers. These studies have, however, summarily dismissed baghouses as a potential control measure because of baghouse size, pressure drop, explosion and fire hazards, and cost.

The high costs and problems experienced during construction and operation of other experimental systems indicate that baghouses may, in fact, be competitive.

2. OBJECTIVE

The objective of this study is to determine if it is feasible to control test cell particulate emissions with baghouse control systems.

3. SCOPE

The scope of this project was defined by the Department of the Air Force, Civil and Environmental Engineering Development Office, Tyndall AFB, Florida.

For simplicity, this investigation will only consider control of the TF30-P100 turbofan engine used in the F-111 aircraft in the military mode of operation. This engine represents the "worst case air handling problem". The primary test cell used to test this engine is located at Tinker AFB, Oklahoma. The design and cost data developed will refer to this specific application.

The following design parameters will be used: particulate control efficiency of 95 percent; particle sized distribution, approximately log normal with a mass median diameter of 0.1 μm; and a geometric standard deviation of 10. Particles are assumed to be pure carbon and approximately spherical.

SECTION II

TEST CELLS

1. PURPOSE

A test cell is a structure which facilitates out-of-aircraft testing of a jet engine after maintenance and/or overhaul. It houses fuel delivery systems, the engine to be tested, the augmenter tube and various devices to allow monitoring of all parameters important in testing the proper operation of the engine. Test cells are maintained by the U.S. Army, Navy and Air Force, civilian airlines and gas turbine manufacturers. When jet engines are tested, some dark, sooty particulate matter (Reference 1) is produced by the gas turbine. These emissions are often visible for a considerable distance and are exhausted to the ambient air via short vertical stacks.

2. TYPES

There are five kinds of test facilities used by the military:

(1) Depot Permanent Test Cells - permanent masonry structures fully instrumented.

(2) Type A Permanent Test Cells - similar to #1 but less instrumentation.

(3) Type C Permanent Test Cells - similar to #1 but no thrust measurement capability.

(4) Demountable Test Cells - metallic construction.

(5) Test Stands - unenclosed frames, exhaust not confined.

There are a total of 130 permanent test cells, 88 demountable test cells and 273 test stands for the Army, Navy and Air Force (Reference 1).

Different types of engines which are tested in these cells are:

(1) Turboprops

(2) Turbojets (both single and dual rotor)

(3) Turbofans

3. USAGE

The tests consist of running the engine for variable lengths of time at various power settings which correspond to "modes" of engine operation. Terms used such as idle, cruise, military and A/B all refer to percentages of engine power. The fact that engines are run through these power settings will make the design of air pollution control equipment more complex. The exhaust flow rate, temperature, particulate composition, moisture content, pressure, particle size distribution and concentration will all vary with the mode of engine operation. For this study certain assumptions have been made to eliminate insignificant variables. These are summarized in the next section.

SECTION III

DESIGN PARAMETERS AND ASSUMPTIONS

1. LOCATION

This study will only consider the design of a control device for Cell Number 4 at Tinker AFB near Oklahoma City, Oklahoma. This affects the design, since the utilities available will influence the cost analysis of control. The location, because of meteorological factors, influences pollutant dispersion.

Tinker AFB is located eight miles southeast of central Oklahoma City, but urban areas extend nearly to the base perimeter (Reference 2). The population within the metropolitan area is approximately 600,000 (Reference 3). The countryside is essentially flat and relatively treeless, making any smoke generated at the base easily observed.

2. METEOROLOGICAL DATA

A test cell incorporates the use of ambient air as a means of cooling the engine exhaust gases. Therefore, the ambient temperature, relative humidity and pressure affect the flow rate through the cell. This data is also significant in design of the structural members of the control device erected at the site (see Table 1).

3. TYPE OF TEST CELL

The subject for this study is a fully instrumented permanent test cell. The design was based on minimizing noise and was constructed in the early 1970's (see Figure 1).

The operational characteristics of the engine being tested can be effected when back pressure exceeds about 20 in. $H_2O$. Current acoustical treatment of the exhaust stream causes a back pressure of about 10 in. $H_2O$ at afterburner power. This means that a control device should not cause an additional pressure drop of greater than 10 in. $H_2O$ (Reference 1).

Any control device considered for jet engine test cells must be able to withstand the very high sound levels existing in the gas exhaust stream. Average sound levels at the augmenter range from 170 dB for a J57 engine up to 180 dB for a J75 engine (Reference 1).

4. AUGMENTATION TUBE

In the test cell the engine is fastened to a thrust frame or stand. This is in turn firmly anchored to the cell. Immediately behind the engine the augmenter tube, so named because it augments the flow of air through the cell, is mounted. This tube serves three purposes:

TABLE 1. DESIGN METEOROLOGICAL DATA
FOR TINKER AFB, OKLAHOMA (References 3 and 4)

| Month | Average Ambient Temperature* (°F) | | Relative Humidity** (%) | |
|---|---|---|---|---|
| | Max | Min | Max | Min |
| January | 48 | 26 | 81 | 49 |
| July | 93 | 70 | 87 | 48 |

Temperature Extremes Recorded: High, 113°F

Low, -17°F

Elevation: 1,285 feet

Latitude: 35° 24' North

Longitude: 97° 36' West

Highest average monthly wind speed: March, 15.4 mph

Prevailing winds: SSE

Fastest one-minute wind recorded: 75 mph

* On a monthly basis

** A six-hour average

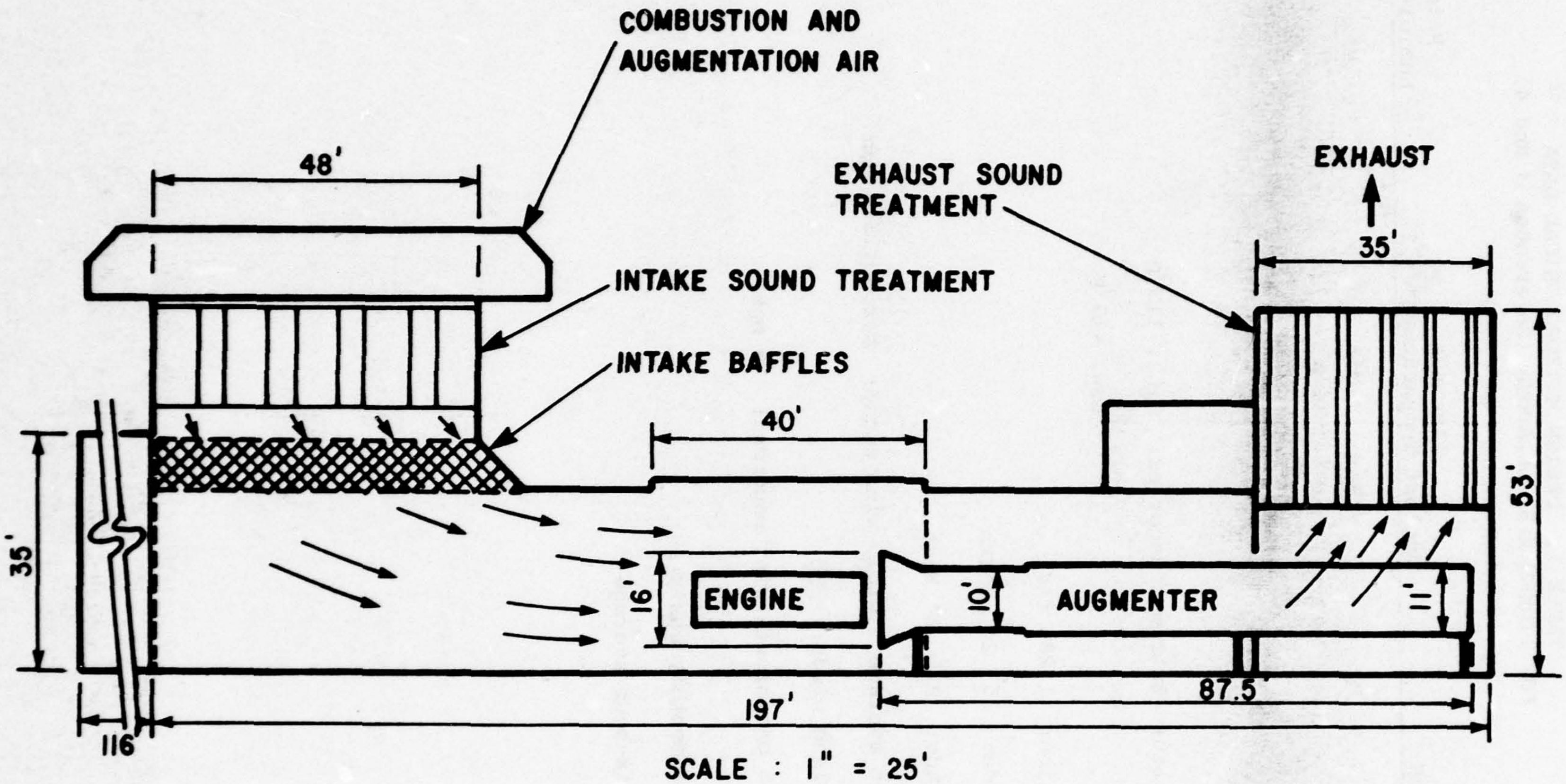



Figure 1. Tinker Air Force Base Jet Engine Test Cell No. 4

(1) It serves as an ejector pump to supply air to the engine.

(2) The air drawn over the engine provides cooling normally obtained by the motion of the aircraft in flight.

(3) The air entrained by the augmenter cools and dilutes the exhaust gases, thereby reducing thermal degradation of the test cell structure. (Temperatures must be kept below 350$^{o}$F to prevent concrete spalling.)

The flow inside the tube is highly turbulent, insuring good mixing. This mixing is caused in part by the swirl present in the turbine exhaust (References 1 and 5) (see Figure 1).

The amount of augmenter air drawn into the cell depends on engine placement and type. The tube has cooling spray rings with nozzles mounted radially to allow a spray of cooling water to be added during high engine power settings. The water also absorbs some acoustic energy generated during high power operation.

Each engine and augmenter tube provide a particular augmentation ratio, i.e., the ratio of the mass of secondary air flow to the mass of engine exhaust gas (Reference 5). For this study, assume no spray water is necessary in military mode operation.

## 5. TYPE OF ENGINE

Assume the engine to be tested is the TF30-P100. This engine is used in the F-111 aircraft.

## 6. OPERATING MODE

Assume design conditions are for "Military Power." The data in Table 2 were given as representative of this engine by the Air Force.

## 7. EMISSION CONCENTRATION

This factor was given by the Air Force as 2.21 pounds of particulate matter per 1000 pounds of fuel.

TABLE 2. TF30-P100 TEST DATA

Engine Type: TF30-P100

Engine SN: 679747

Barometric Pressure: 28.69 in. Hg

Ambient Temperature: 59.0°F

Fuel: JP-4

Fuel Sulfur: 0.05%

Mode 4: Military Power

Thrust: 14368 lb

Fuel Flow: 9220 lb/hr

Air Flow: 856800 lb/hr

Actual F/A Ratio: 0.011

Exhaust Gas Temperature: 579.1°F

Exhaust Gas Pressure: 28.4 psia

Particulate Emission Factor: 2.21 lb/1000 lb fuel

SECTION IV

TEST CELL EMISSIONS

1. FUEL

The fuel for this design is JP-4, a blend of gasoline and kerosene stocks, with an average boiling point of 140$^{o}$F and a distillation end point of 470$^{o}$F. Antioxidants, corrosion inhibitors and metal deactivators are used in jet fuels, and an icing inhibitor is specified for JP-4 (MIL-1-27686). The heat of combustion (lower or net) maximum is 18,400 Btu/lb. The aromatics maximum volume percent is 25.0, and olefins maximum volume percent is 5.0. The maximum sulfur content is 0.05 percent.

2. GASEOUS EMISSIONS*

Most data on gaseous emissions have been collected at the engine tailpipe or somewhat down stream. Little data have been obtained by sampling at the test cell exhaust stack exits.

Data published in 1970 summarized some previous publications which showed turbofan engine emission factors at a 100 percent power setting (see Table 3). This test data was not taken at the stack exist. Due to difficult testing conditions at the stack exit, sampling has traditionally been performed at other locations within the test cell. These factors, however, can be used with the fuel flow rate to determine a rough estimate of pollutant emissions.

In general, any combustion process results in the formation of the oxides of nitrogen. Only two of the several possible oxides, nitric oxide (NO) and nitrogen dioxide ($NO_2$), are present in sufficient amounts to be considered (Reference 1).

Jet engine sulfur oxide emissions, principally $SO_2$, are very low due to the low sulfur content of the fuel. Therefore, these will be neglected.

Incomplete combustion results in unburned hydrocarbons (UHC). These include gases and condensible vapors. Jet engines usually emit the highest concentrations of UHC at idle, and maximum amounts in the after-burner mode. These can condense if the gases are cooled enough prior to release. This condensation increases particulate emissions.

Carbon monoxide is also present as a result of incomplete combustion. This pollutant falls to insignificant levels at high power settings (Reference 1).

---

*Although gaseous emissions are not of primary concern in this report, mention of them is made for completeness and consideration in the explosion potential evaluation.

TABLE 3. TURBOFAN EMISSION FACTORS

| Pollutant | Emission Factor (Reference 6) lb/1000 lb Fuel | Std. Dev. | Emission Factor lb/1000 lb Fuel |
|---|---|---|---|
| CO | 0.84 | ± 0.4 | 3.1 |
| HC | ---- | ----- | 0.165 |
| HC(as C) | 0.24 | ± 0.14 | ----- |
| $NO_x$ | ---- | ------ | 26.9 |
| $NO_x$(as $NO_2$) | 2.4 | ± 1.14 | ------ |
| Particulate | 1.62 | ± 0.83 | 2.21 |
| $SO_x$ | ---- | ------ | 1.0 |

* These data were at a fuel flow rate of 7120 lb/hr.

## 3. PARTICULATE EMISSIONS

In general, particles less than 1 μm in diameter are formed in combustion processes. Smokes are typically in the range of 0.001 to 0.3 μm diameter and combustion nuclei are about 0.01 to 0.1 μm diameter (Reference 14). However, some larger particles are emitted from this source due primarily to scouring (breaking off of deposits on the augmenter and cell wall). The combustion process can be divided into three phases: cracking, carbon formation and oxidation. During cracking the long, straight chain molecules are broken into small fragments by the hot flame front. These fragments are easily oxidized and thus, little soot forms in the primary zone. Branched or ring hydrocarbons, however, lose hydrogen rather than cracking, thus forming unsaturated hydrocarbons which condense in the oxygen-lean surroundings to form soot precursors. In carbon formation these polyunsaturated hydrocarbons act as nucleation centers for polymerization. This process proceeds rapidly to form increasingly larger particles. The last phase, oxidation, is a rapid reaction involving the initial addition of oxygen to the hydrocarbon molecule, leading to its fragmentation. If each molecule had unlimited access to oxygen, carbon formation would not take place. However, the smaller fragments and the soot formed in the fuel-rich primary zone compete for the limited oxygen (Reference 5).

The composition of soot particles is approximately 96 percent (wt) carbon, most of the remainder being oxygen and hydrogen (Reference 5). Data collection is difficult due to the extreme conditions at the engine exhaust and at the stack outlet. Stacks are, in general, from 200 to 900 square feet, with irregular velocity distribution (see Figure 2). The noise baffles severely affect the flow (see Figure 1) and restrict testing of the cell exhaust.

There have been several attempts to obtain representative samples from jet engine test cells. The objective of this sampling has been twofold:

(1) to obtain an accurate particle size distribution

(2) to quantify emission factors

The particle size distribution varies according to the engine operating mode. Particle size is necessary to define the collection mechanisms employed in the design of a particulate control device.

Emission factors are needed to accurately predict the test cell effects on the surrounding area. Emission factors are also used to predict loading and cleaning cycles in the control device.

Tables 3, 4, and 5 (from Reference 5) summarize emission data for several test cell operations.

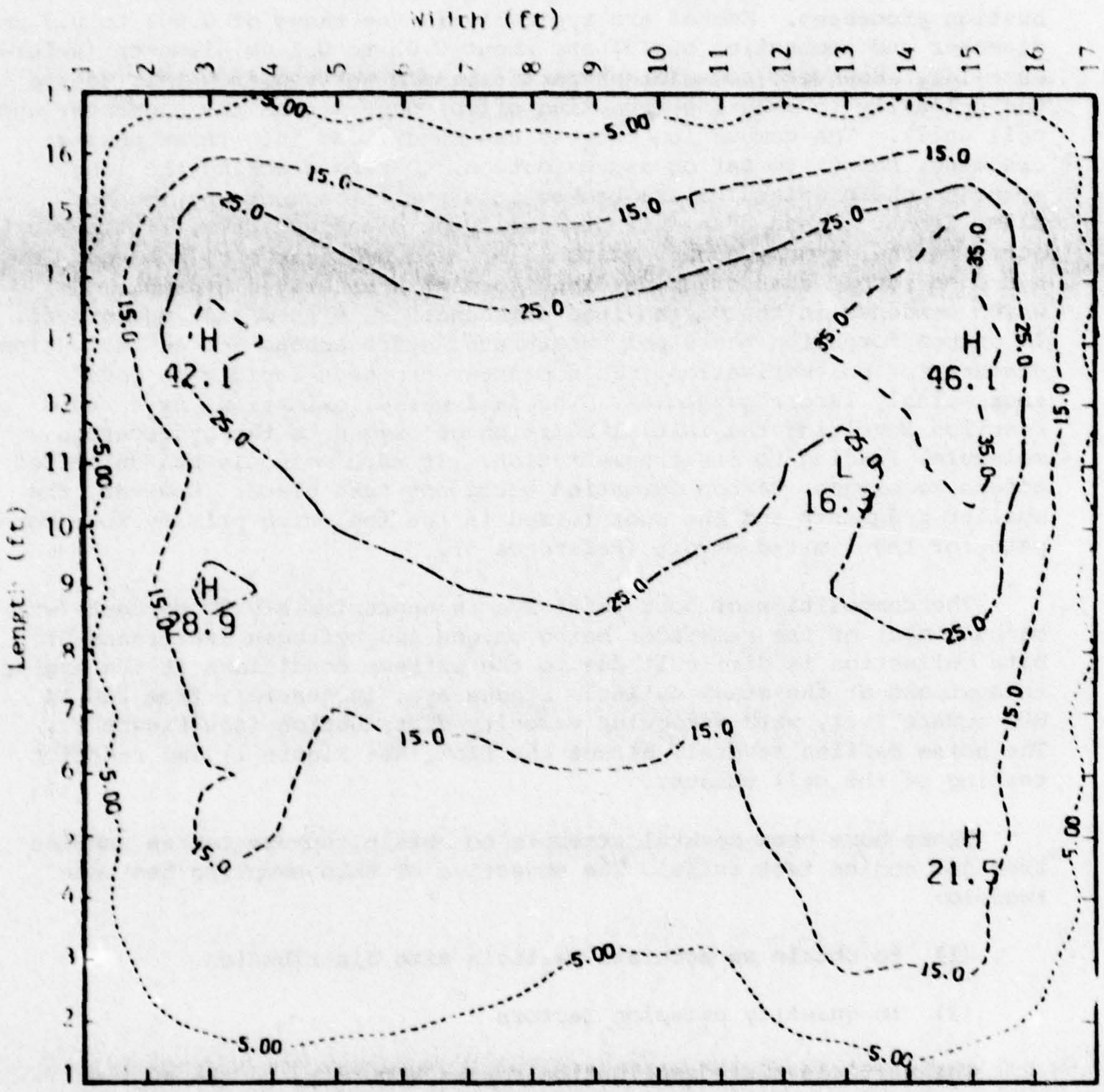



**Figure 2. J-57 Test Cell Exhaust Velocities at Military Power (ft/sec) Plan View (Reference 7)**

TABLE 4. RANGE OF EMISSIONS FROM TINKER AFB TEST CELLS

(Reference 5)

POLLUTANT/CELL

| | | PARTICULATES | | | | UNBURNED HYDROCARBONS | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 1b/run | | 1b/day[1] | | 1b/run | | 1b/day[1] | |
| Engine | Mode | Min. | Max. | Min. | Max. | Min. | Max. | Min. | Max. |
| J79 | Idle | 4.8 | 33.5 | | | 4.8 | 21.0 | | |
| | Normal | 80.6 | 143.5 | | | --- | 1.5 | | |
| | Military | 61.1 | 190.0 | | | --- | 10.6 | | |
| | A/B | 68.5 | 94.3 | | | 16.5[2] | 16.5[2] | | |
| Total | | 213.0 | 461.3 | 639.0 | 1383.9 | 21.3 | 49.6 | 63.9 | 148.8 |
| J[illegible] | Idle | 0.5 | 1.3 | | | 74.3 | 147.5 | | |
| | Normal | NA[3] | NA[3] | | | 2.2[2] | 2.2[2] | | |
| | Military | 6.6 | 16.5 | | | 1.1 | 5.5 | | |
| | A/B | NA[3] | NA[3] | — | — | NA[3] | NA[3] | — | — |
| Total | | | | | | | | | |
| [illegible] | Idle | 0.2 | 14.1 | | | 7.1 | 145.0 | | |
| | Normal | NA[3] | NA[3] | | | 1.8 | 3.6 | | |
| | Military | 5.0 | 100.7 | — | — | 0.8 | 12.6 | | |
| Total | | | | | | 9.7 | 161.2 | 38.8 | 624.8 |
| [illegible] 33 | Idle | 0.5 | 13.1 | | | 91.6 | 269.0 | | |
| | Normal | 249.0[2] | 249.0[2] | | | --- | 25.0 | | |
| | Military | 5.1 | 119.0 | | | --- | 9.5 | | |
| Total | | 254.6 | 381.1 | 763.8 | 1113.3 | 91.6 | 303.5 | 28.8 | 910.5 |
| TF30 | Idle | 17.4 | 56.4 | | | 3.6 | 63.4 | | |
| | Normal | 64.0 | 65.0 | | | 2.0[2] | 2.0[2] | | |
| | Military | 19.5 | 115.2 | | | 0.5 | 14.1 | | |
| | A/B | 310.0[2] | 310.0[2] | | | 115.4 | 2360.0 | | |
| Total | | 410.9 | 546.6 | 410.9 | 546.6 | 121.5 | 2439.4 | 121.5 | 2434.4 |

1. Based on average runups/day
2. Only one emission factor available
3. Not available

TABLE 5. SUMMARY OF SOURCES OF EMISSIONS MEASUREMENTS (Reference 5)

| Test Organization | Test Site | Type Engines Tested | Type Emission Measurement |
|---|---|---|---|
| Pratt and Whitney Aircraft | E. Hartford CT | JT3D, JT8D, JT9D - Turbines (Experimental and Production Types) | All Emissions - Wet |
| Detroit Diesel Allison Div | Indianapolis IN | T56 (Production Types) - Turboprops | CO, $CO_2$, $NO_x$, Dry<br>HC - Wet |
| Teledyne-Continental | Muskegon MI | Light Utility, General Aviation - Piston | CO, NO - Dry<br>HC - Wet |
| AiResearch | Phoenix AZ | Auxiliary and Small Propulsion Units | All Emissions - Wet |
| Bureau of Mines | American Airlines Maint. & Engrg Ctr, Tulsa OK | JT3D, JT8D, R-R Spey - Turbines | All Emissions - Wet |
| EPA Team | United Airlines San Francisco CA | JT3C, JT3D, JT4A, JT8D - Turbines | All Emissions - Wet |
| Southwest Research Institute | Kelly AFB TX<br>TWA, Kansas City MO | T56 - Turboprops, J79 - Turbines<br>JT4A, JT3D, JT8D, CJ805 - Turbines | All Emissions - Wet<br>All Emissions - Wet |
| Scott Research Laboratories | Norfolk NAS VA<br>General Aviation Arpts | J52, J57, TF30 - Turbines<br>Light Utility - Piston | All Emissions - Dry<br>All Emissions - Dry |

A fundamental assumption in the particle analysis is that particles are spherical. This has been verified with electron photomicrography, which showed that soot particles from jet engines are more or less spherical. Usually several particles are grouped together to form a chain (Reference 1).

The particle size distribution is assumed to be log normal. The mass median diameter is approximately 0.1 μm diameter and the geometric standard deviation is 10 (see Figures 3 and 4). Using this information and the particulate emission factor of 2.21 pounds per 1000 pounds of fuel and typical emission regulations of 0.1 pounds particulate per million Btu's, analysis can be made for percent control required to meet the mass emission standard. To comply with this mass regulation, only 17 percent efficiency is required (see below).

MASS REGULATIONS

Allowable

$$\frac{0.1 \text{ lb part}}{10^6 \text{ Btu}} \left(\frac{9220 \text{ lb fuel}}{\text{hr}}\right) \frac{184000 \text{ Btu}}{\text{lb fuel}} \approx 17 \text{ lb part/hr}$$

Emission Factor

$$\frac{2.21 \text{ lb part}}{1000 \text{ lb fuel}} \quad \frac{9220 \text{ lb fuel}}{\text{hr}} \approx 20.4 \text{ lb/hr}$$

Control Needed

$$\text{Percent Efficiency} = \frac{20.4 - 17}{20.4} (100) = 17\%$$

Visible Emissions (typical regulations are <20% opacity) - compliance would require more stringent control.

These calculations show that if 100 percent of the particles greater than 1.0 μm diameter were collected (see Figures 3 and 4), the mass regulation would be satisfied. However, regulation of 20 percent opacity is much more stringent. This requires control of particles in the range of 0.01 μm diameter to 1.0 μm diameter. To assure compliance with opacity regulations, a 95 percent control efficiency is desired by the Air Force.

## 4. NOISE

The baghouse under consideration will have to maintain the present level of noise control.

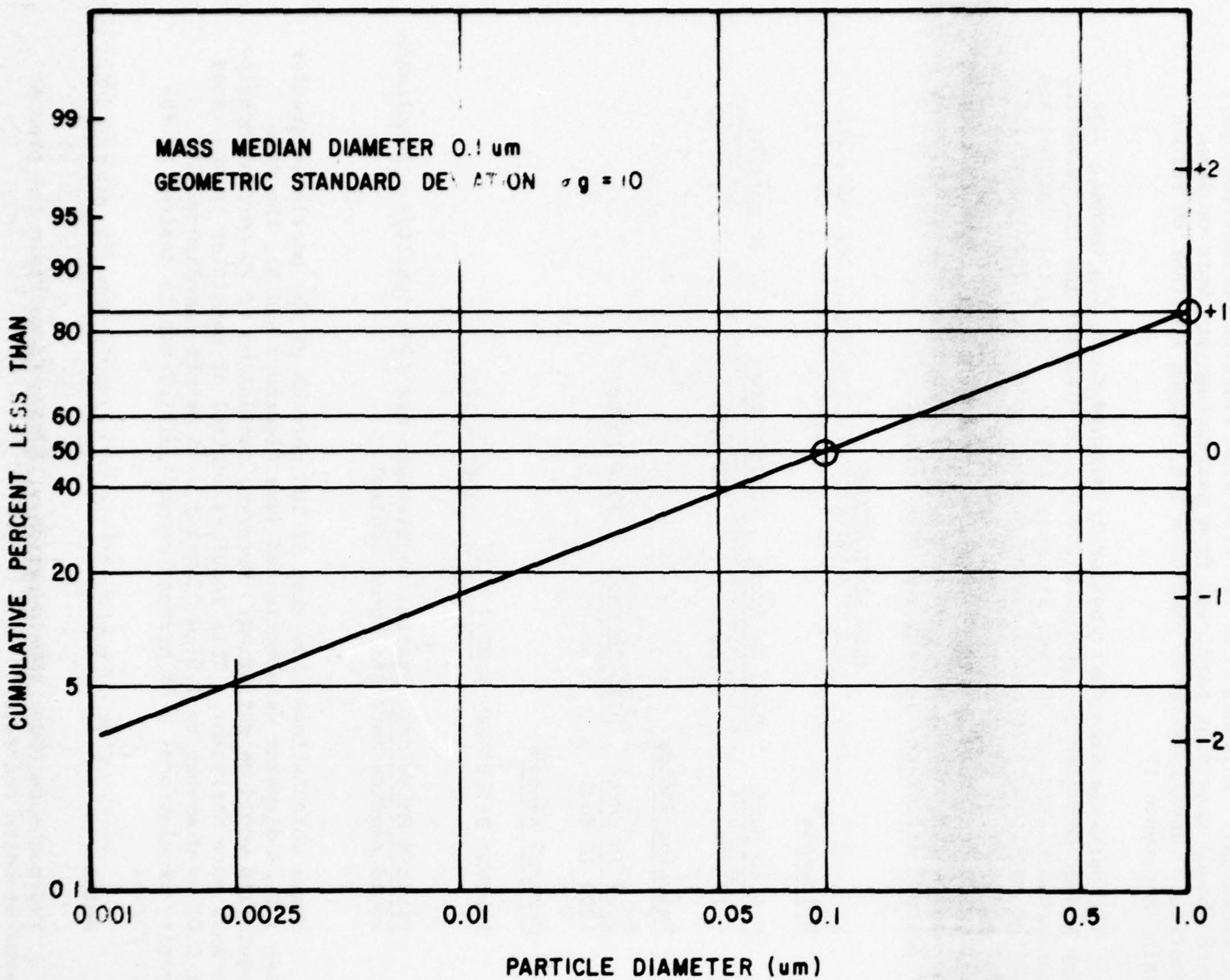



Figure 3. Test Cell Particle Size Analysis

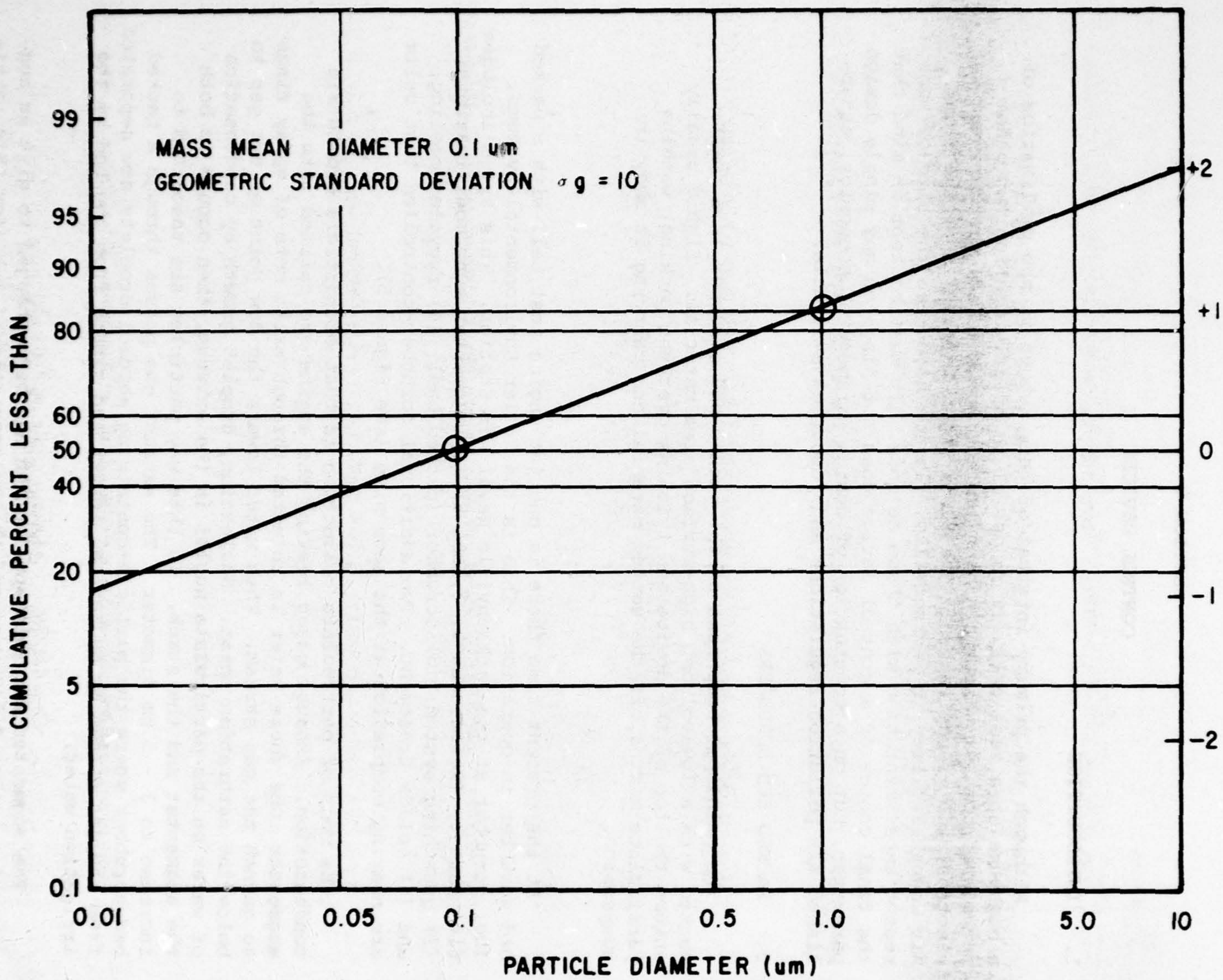



Figure 4. Test Cell Particle Size Analysis

SECTION V

CONTROL DEVICES

1. INTRODUCTION

Although the primary interest of this report is the utilization of a baghouse on a test cell, it is useful to briefly mention two other methods of control which have been tested: packed bed scrubbers and wet electrostatic precipitators. The Black Point Test Cells at the Naval Air Rework Facility in Jacksonville, Florida have been the site of some recent experimentation with these methods. It must be kept in mind that the final choice of a control device does not hinge on any single design parameter, but on a combination of design parameters, economics, established air pollution regulations and resources available.

2. PACKED BED SCRUBBERS

The principal component of the packed bed scrubber is a tower packed with a low-volume, high-surface area material. Liquid usually enters the top of the device and trickles over the packing, washing particulate matter off the wetted material and carrying it away in suspension.

At the present time there is one jet engine test cell with a packed bed scrubber in operation. This is the Teller Environmental Systems, Inc. scrubber at the Jacksonville Naval Air Station. This sytem includes five parts: (References 5, 7, and 8) (1) augmenter tube modifications; (2) quenching system; (3) scrubber (packed bed); (4) recycled cooling; and (5) solids treatment. Two additional scrubber-controlled test cells are nearing completion at the same site (see Figure 5).

The mode of particulate collection is that of particle growth via condensation. Exhaust gases leaving the engine are carried into the augmenter tube where water is injected through extra sets of spray rings to quench the gas stream. This water lowers the dew point of the gas to below the saturation point. Nucleation, droplet growth by condensation of water on the particulate nuclei in the exhaust, then occurs in both the augmenter and the stack. In this way particles are theorized to increase to 3 - 5 μm diameter. The exhaust gas passes through a packed bed scrubber where the particle-containing aerosol droplets are separated from the gas stream by mechanical forces and rinsed from the bed by the irrigation water.

The augmenter for this application has been changed to give an augmentation ratio of 1.0 compared to the conventional 2.5 (for this particular cell). This modification significantly reduces the flow rate of gas to be cleaned.

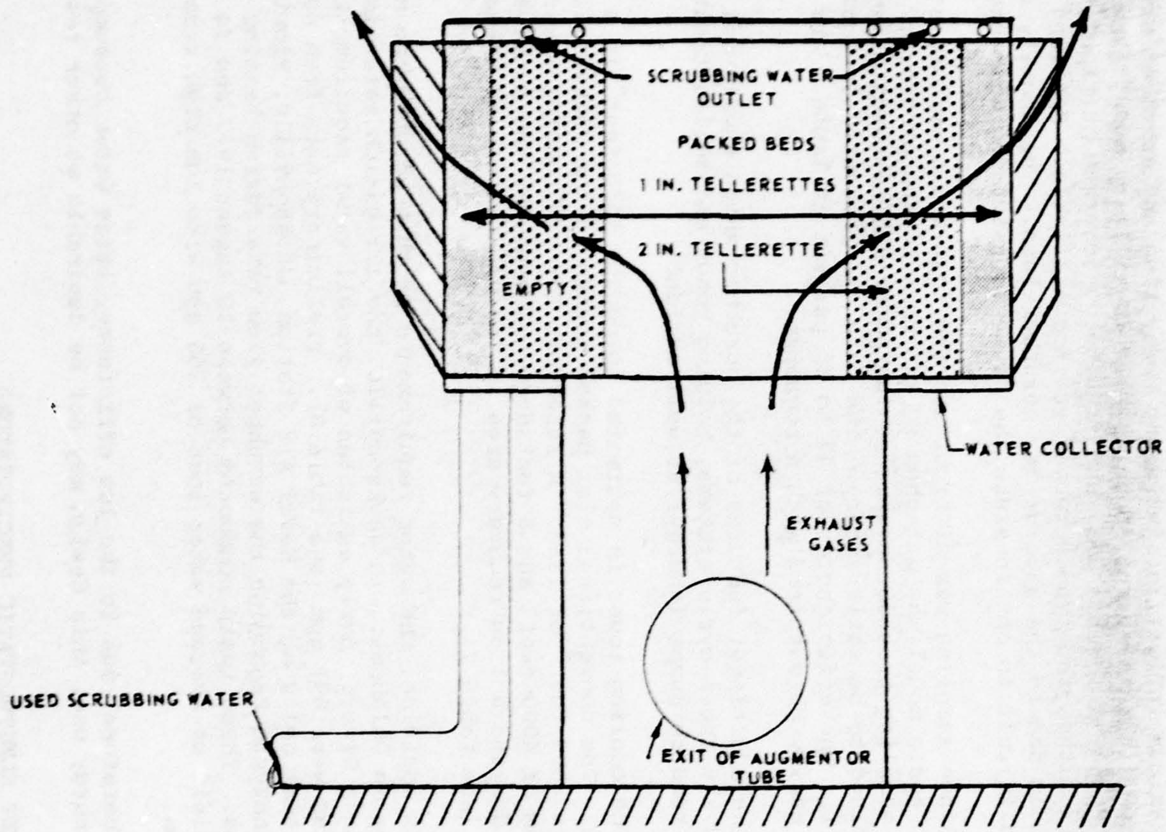



Figure 5. Schematic of Teller Scrubber (Reference 5)

At the top of the stack, turning vanes direct the gas horizontally into two packed scrubbing beds constructed on the periphery of the stack. Each bed is 30 feet long by 18 feet high by 6 feet thick. The inner 5½ feet of each bed consists of 2-inch Tellerettes, a proprietary packing material, while the outer 6 inches is a demisting section of 1-inch Tellerettes.

Maximum irrigation, including spray ring and scrubber water, is 8300 gpm (in after-burner mode), while in military mode, flow is reduced to 4000 gpm (Reference 1). Unfortunately, accurate particulate emission data from the prototype scrubber are not available. Sampling is extremely difficult due to the size of the scrubber face. The opacity reading is also difficult to obtain since the plume is saturated with steam.

Since sampling was difficult on the full-scale prototype scrubber, a 1/50 scale model was attached to the back of the prototype. Pilot model sampling procedures were evaluated by EPA representatives and were determined to be satisfactory. The data are presented in Table 6 (Reference 1). The efficiencies of 47 to 85 percent in Table 6 are lower than might easily be obtained with a baghouse.

The additional features of the scrubber which should not be overlooked are the recycle systems, holding ponds and solids treatment. All these require pumps (energy) as well as land.

The cooling tower is estimated to occupy 1130 feet$^2$ in a circular design. The conventional slat packed towers at the Jacksonville location require 2000 feet$^2$ of land. A reservoir for the cooling tower must be a minimum of 4000 feet$^2$ and 8 feet deep. Therefore, the total area required (provided the solids recovery area is included in one of these) is 6627 feet$^2$ (see Table 7).

In addition, the water requirements of this scrubber do not favor its use in Oklahoma. In Jacksonville, the irrigation water is from the St John's River. Early estimates of overall water requirements for a turbofan were 691 gpm (see Table 8). Preliminary data from new full-scale test cells at the Naval Air Station, Jacksonville, Florida have been analyzed regarding the scrubber flow rate during testing of various engines. These tests conducted between 30 August 1977 and 14 October 1977 yield an average water loss of 266 gpm with the high recorded as 766 gpm.

Therefore, due to the low efficiency, large water consumption and high energy use, this design may not be desirable at other test cells.

## 3. WET ELECTROSTATIC PRECIPITATORS

Wet electrostatic precipitators (ESP) are considered in this study because of the high performance nominally attributed to them. They

TABLE 6. TEST RESULTS ON PILOT SCRUBBER AT THE BLACK POINT NO. 1 TEST CELL AT JACKSONVILLE NAVAL AIR STATION, USING A J79 ENGINE (Reference 1)

| | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet |
|---|---|---|---|---|---|---|
| Date | 1-30 | 1-30 | 1-31 | 1-31 | 2-1 AM | 2-1 AM |
| No. ft. of packing | 3 | | 3 | | 3 | |
| Engine operating condition | Normal Rating | | Normal Rating | | Normal Rating | |
| Flow at #1 Sump gal./min. | 12.3 | | 16.2 | | 14.7 | |
| Flow at #2 Sump gal./min. | .2 | | .5 | | 75.0 | |
| Vol. of dry gas sampled, SCF | 73.04 | 62.75 | 91.46 | 85.15 | 91.89 | 75.01 |
| Stack flowrate, SCFM, dry | 6539.8 | 5448.0 | 8919.5 | 8075.4 | 9046.4 | 7510.6 |
| Stack gas velocity, at stack conditions, f.p.m. | 542.4 | 437.1 | 746.1 | 638.8 | 760.4 | 566.4 |
| Moisture, % by volume | 16.6 | 14.1 | 17.4 | 12.9 | 17.7 | 10.5 |
| Stack gas temp. degree F. | 129.6 | 126.8 | 130.2 | 127.6 | 131.0 | 115.4 |
| Isokinetic sampling rate, % | 104.4 | 107.7 | 95.9 | 98.60 | 95.0 | 93.4 |
| <u>Particulate Results</u> | | | | | | |
| (a) <u>Probe and filter catch</u> Grains/SCF, dry, x $10^{-3}$ | 6.90 | 3.09 | 6.67 | 2.53 | 6.55 | 3.20 |
| (b) <u>Total catch</u> grains/scf, dry, x $10^{-3}$ | 7.27 | 3.41 | 6.85 | 2.68 | 7.06 | 3.74 |
| (c) <u>Particulates from #1 Sump water sample</u> grains, scf, x $10^{-3}$ | 10.69 | | 9.33 | | 9.30 | |
| <u>Particulate Removal Efficiency</u> | | | | | | |
| Based on air sample (a), % | 55.2 | | 62.0 | | 51.2 | |
| Based on air sample (b), % | 53.1 | | 60.9 | | 47.0 | |
| Based on total (air and water, a+c), % | 82.4 | | 84.2 | | 79.8 | |
| Based on total (air and water, b+c), % | 81.0 | | 83.5 | | 77.2 | |
| Entrained Water Removal, % | 42.5 | | 75.3 | | 67.0 | |

TABLE 7. SCRUBBER LAND AREA REQUIRED (Reference 1)

| Unit | Area ($ft^2$) |
|---|---|
| Scrubber (22 ft x 28.5 ft) | 627 |
| Cooling Tower | 2000 |
| Reservoir | 4000 |
| Total | 6627 |

TABLE 8. SCRUBBER-OVERALL WATER REQUIREMENTS (Reference 9)

| System | Flow Rate (gpm) |
|---|---|
| Quench Loss | 1007 |
| Cooling Tower Loss | 250 |
| Subtotal | 1257 |
| Recovery in Scrubber | 566 |
| Average Net Loss per Test | 691 |

can be used when particles are less than 20 μm diameter, and are capable of handling volumes of up to 2 ($10^6$) actual cubic feet per meter (acfm). Operating temperatures extend up to 750°F, and the pressure drop experienced is on the order of 0.1 to 0.5 inches of $H_2O$ (Reference 5).

Gas velocity commonly ranges up to 500 ft/min. For this design of 800,000 acfm, the required precipitator cross-sectional area would then be 1600 feet$^2$. The ESP was tested in Jacksonville on a 1/65 full-scale model.

A fairly extensive series of tests were performed with the results shown in Table 9 (Reference 1). The following reasons are the most likely to have caused the low efficiencies (52 to 89 percent): (1) The gas velocities were 500 fpm (this is the velocity at the top of the operating range), (2) Small particles did not have time to migrate to the collection plates, and (3) Operating problems, e.g., shorting due to excessive $H_2O$ carryover, long cleaning cycles and difficulties in removing particulate from the plates.

The wet precipitator may be an acceptable alternative to scrubbers; however, in addition to the above mentioned problems, the requirement to treat the precipitator effluent is another disadvantage. Although this device presents a possible alternative, its practical use has not been demonstrated to date.

TABLE 9. EMISSION DATA FROM THE ELECTROSTATIC PRECIPITATOR AT JACKSONVILLE NAVAL AIR STATION, BLACK POINT NO. 1 TEST CELL - J79 ENGINE (Reference 1)

| | Inlet | Outlet | Inlet | Outlet | Inlet | Outlet |
|---|---|---|---|---|---|---|
| Date | 4-17 | 4-17 | 4-18 AM | 4-18 AM | 4-18 AM | 4-18 AM |
| Scrubber water flow at #1 sump gal/min | 9.66 | | 9.89 | | 9.61 | |
| Vol. of dry gas sampled, scf | 92.79 | 81.66 | 87.99 | 83.31 | 84.27 | 84.82 |
| Stack flowrate, scfm, dry | 9276.0 | 8149.4 | 8404.3 | 7621.5 | 8607.6 | 7920.2 |
| Stack gas velocity, at stack conditions, fpm | 763.8 | 665.8 | 703.8 | 620.5 | 698.0 | 698.3 |
| Moisture, % by volume | 15.75 | 15.15 | 17.13 | 14.89 | 16.66 | 15.39 |
| Stack gas temp. degree F. | 132 | 131 | 132 | 131 | 132 | 131 |
| Isokinetic sampling rate, % | 97.5 | 97.6 | 102.0 | 106.0 | 95.0 | 104.3 |
| Particulate Results | | | | | | |
| (a) Probe and filter catch grains/scf dry, x $10^{-3}$ | 6.17 | 2.90 | 3.48 | 1.05 | 3.14 | 1.05 |
| (b) Total catch grains/scf, dry, x $10^{-3}$ | 7.30 | 3.54 | 3.92 | 1.20 | 3.21 | 1.27 |
| (c) Particulate from #1 sump water sample grains/scf x $10^{-3}$ | 5.41 | | 5.64 | | 5.14 | |
| Particulate Removal Efficiency | | | | | | |
| Based on air sample (a), % | 53.0 | | 69.8 | | 66.6 | |
| Based on air sample (b), % | 51.5 | | 64.9 | | 60.4 | |
| Based on total (air and water, a+c), % | 74.9 | | 88.5 | | 87.3 | |
| Based on total (air and water, b+c), % | 72.1 | | 86.8 | | 84.8 | |
| Entrained Water Removal, % | 11.5 | | 44.8 | | 22.7 | |

SECTION VI

FACTORS AFFECTING DESIGN OF A BAGHOUSE

1. GAS FLOW RATE

Various properties of the carrier gas must be assessed prior to selection of the control equipment. One of the most important of these is the gas flow rate. The test cell involves combustion air, fuel, combustion products, excess air and augmentation air.

The data in Table 2 are used in combustion calculations to obtain the total air flow per minute (see Appendices A - D). These data are summarized in Figure 6.

2. VARIABILITY OF GAS FLOW RATE

The flow rate during a typical engine testing is quite variable. Although this study assumes operation at military mode only, the engine is run at various power settings several times throughout the course of a test. Figure 7 shows one typical test pattern (Reference 9). Information on engine utilization in the test cells at Tinker AFB is given in Table 10 (Reference 5). Appendix E illustrates the calculations used to arrive at the usage rate of the Tinker cells. There are two test cell complexes at Tinker AFB, each one housing four test cells in a side-by-side configuration. Each test cell complex is utilized for approximately 2768 hours of testing per year. This means that one baghouse could possibly meet the requirements of an entire test cell complex. Tinker AFB would then require only two baghouses handling the eight cells.

The exhaust air volume could be reduced by using one spray ring and cooling down the exhaust gas stream. However, the temperature should be kept about 100°F above the dew point to prevent condensation on the bags. See Appendix F and Table 11 for an example addition of a spray ring.

3. COMBUSTIBILITY

Within the baghouse the concentration of vapors must be kept below the lower explosive limit, and temperatures should be kept below 500°C (932°F). This temperature is a common ignition temperature of carbonaceous dust clouds (Reference 10).

The lower and upper limits of flammability indicate the percentage of combustible gas in air, below and above which flames will not propagate. When a flame is initiated in mixtures having compositions within these limits, it will propagate, thus making the mixtures flammable. Early indications show that the carbon concentration of the exhaust gas is low enough to preclude the formation of flammable hydrocarbon. The

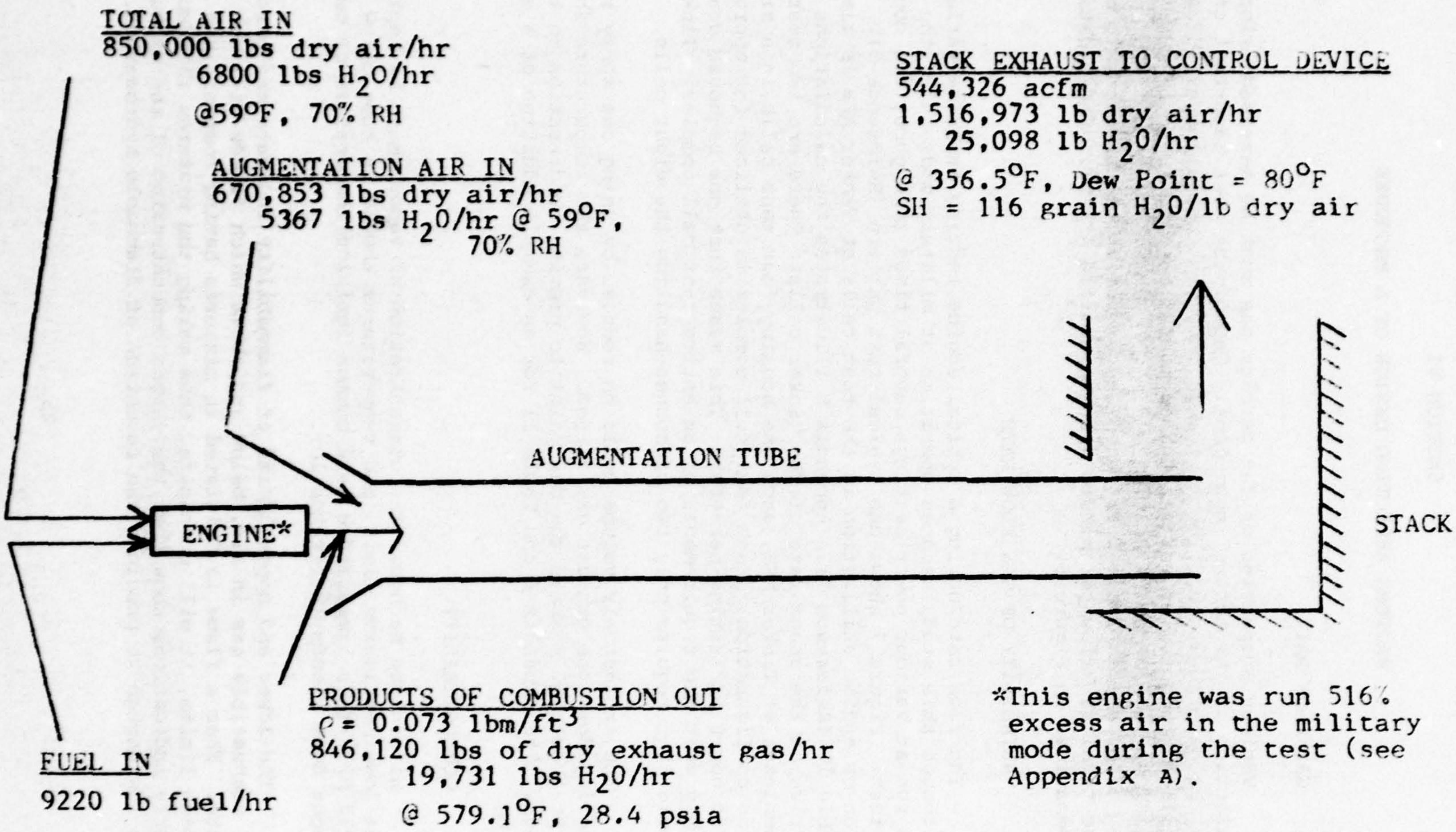



Figure 6. Combustion and Gas Flow Calculation Results

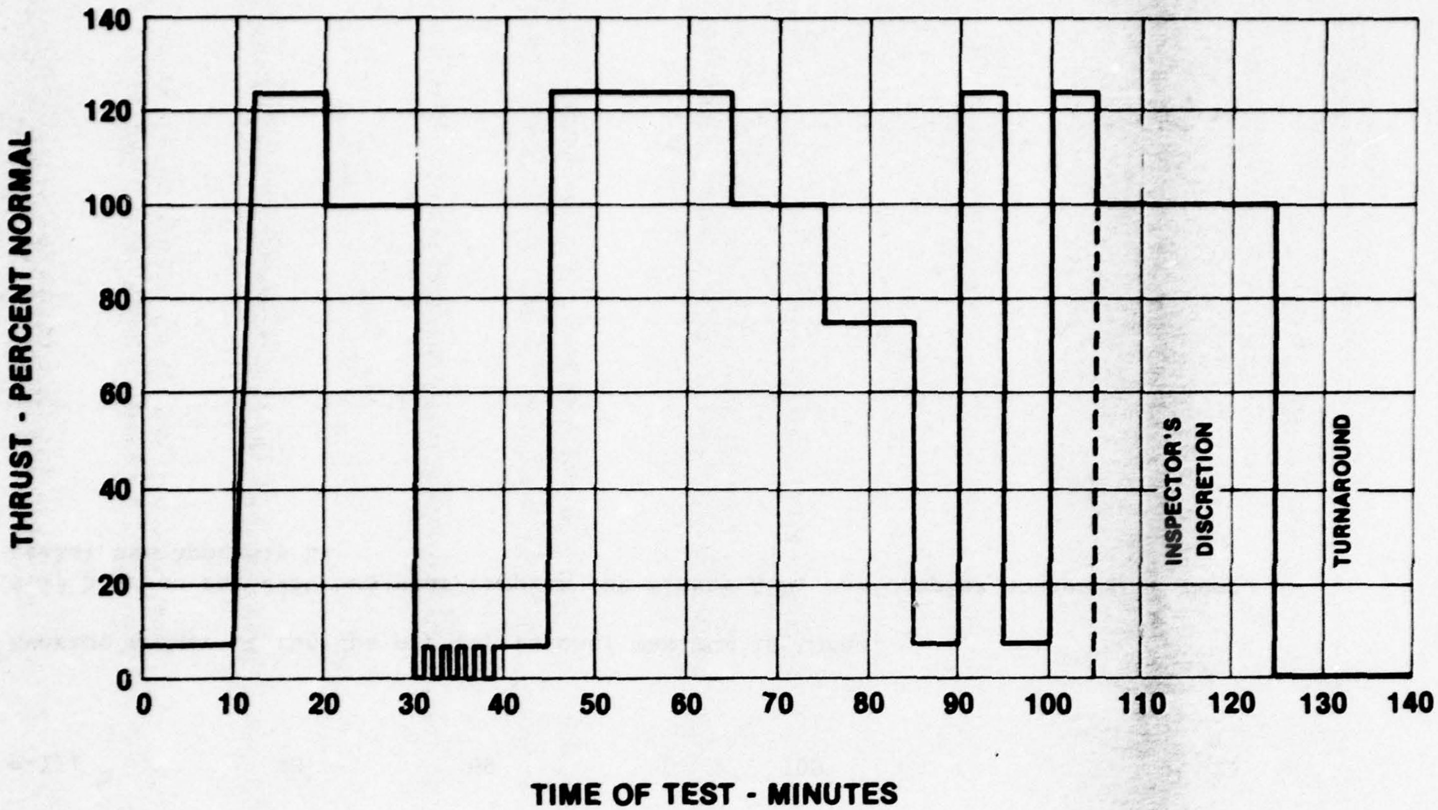



Figure 7. Typical Test Pattern - Norfolk NARF (Reference 9)
TF-30

TABLE 10. TINKER AFB ENGINE RUN-UP DATA (Reference 5)

| TF 30 | Average Time of Run (Minutes) | | | |
|---|---|---|---|---|
| Version | Idle | Cruise (75%) | Take-off (95%-100%) | Max A/B |
| Unknown [a] (Tinker AFB) | 102 | 184 | 41 | 81 |
| F-111 [b] | 48 | 69 | 108 | 23 |

[a] Average number of run-ups per day is one; maximum is three.

[b] 4.13 hrs/run for 2750 hrs/year/complex (at Tinker AFB, one complex houses four test cells) see Appendix E.

TABLE 11. SPRAY RING EFFECT

| Parameter at Stack Exhaust | Without Spray | With Spray |
|---|---|---|
| Temp ($^oF$) | 356.5 | 200 |
| Dew Point ($^oF$) | 80 | 105 |
| Humid Volume ($ft^3$/lb d.a.) | 21 | 18 |
| Water Vapor ($ft^3$/lb) | 32.0 | 26.5 |
| Actual Flow Rate ($ft^3$/min) | 544,326 | 488,592 |
| Spray Ring $H_2O$ Flow Rate (gpm) | 0 | 102 |

greatest hydrocarbon concentration observed in exhaust gas has been 1200 ppm. This is 0.12 in volume percent or well below the lower flammability limits of the expected compounds. Some of the potential compounds along with their limits of flammability are noted in Table 12.

Prior to construction of a full-scale baghouse, measurements of these concentrations should be taken and calculations made to assure that the exhaust air provides enough dilution air (Reference 11). In the event that the margin of safety is not great enough, monitors for these compounds should be included in the design. These concentrations will be present during engine testing as well as from the residual deposits of material on the bag fabric. Therefore, consideration must be given to the concentration inside the baghouse due to the residual deposits when the baghouse is not in operation.

## 4. CONCENTRATION

When designing a baghouse, high and low mass concentrations are taken into consideration. This could affect the cleaning procedures, maintenance, efficiency and disposal. Appendix G has the calculations for mass concentrations. Appendix H shows the emissions per year with and without a control device.

## 5. PRESSURE DROP

The pressure drop through the baghouse is important in this application and will be considered later in more detail. Since the test cell design is restricted by the maximum acceptable engine back pressure, some methods of control are eliminated by this consideration alone (i.e., venturi scrubbers).

TABLE 12. FLAMMABILITY LIMITS

| Compound | Flammability Limits Vol % in Air Mixture: lower | higher |
|---|---|---|
| methane | 5.3 | 14.0 |
| hexane | 1.2 | 7.5 |
| paraffins $C_8H_{18}$ | 0.98 | ---- |
| paraffins $C_9H_{20}$ | 0.85 | ---- |
| monoolefins: | | |
| ethene $C_2H_4$ | 2.7 | 34 |
| propene $C_3H_6$ | 2.0 | 10 |
| carbon monoxide | 12.5 | 74.2 |

## SECTION VII

## BAGHOUSES

### 1. INTRODUCTION

Baghouses are the most widely used industrial device for separating dust from a gas stream. Particles are deposited onto the clean fabric filter by means of interception, impingement, diffusion and electrical forces. As the fabric is subjected to the gas flow, the collected particulate forms an accumulated cake of material on the fabric. Once the cake is established, collection by sieving is possible.

The reasons for baghouse popularity are:

(1) high efficiency

(2) capability to filter out submicron particles

(3) effectiveness even when gas properties and process conditions vary

(4) low energy requirements (in this design)

(5) capability of high temperatures (555$^{\circ}$F; some reports state up to 600$^{\circ}$F)

In the past, fabric filters have been summarily dismissed due to high test cell exhaust temperatures, space considerations, excessive pressure drop and explosion hazards. As is well known, the cost of energy is rising drastically every year. Therefore, some of the other high energy-consuming control methods are now becoming less competitive.

For this application, baghouses are a viable alternative for these following reasons:

(1) Baghouses consume low energy.

(2) They can withstand temperatures exhausted from a TF30-P100 in a test cell.

(3) Dilution air (i.e., augmentation air) is all that is used to provide cooling; the TF30 does not use $H_2O$ cooling in the augmenter tube (Reference 5).

(4) The amount of augmentation air more than sufficiently dilutes the airstream (which was not initially flammable) to assure inflammability.

(5) Baghouse design can eliminate danger from sparks.

## 2. SPECIFIC DESIGN FEATURES

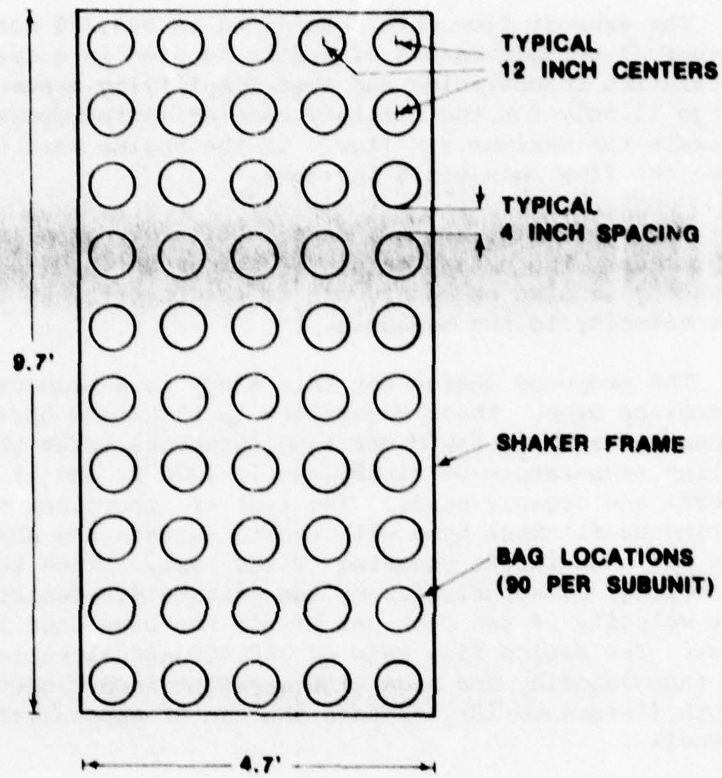
The exhaust flow rate determined is 544,326 acfm (see Appendix C). However, a certain margin of safety is used in a design to allow for calculation inaccuracies and over-simplifying assumptions. Also, this design is only for the military mode of engine operation which does not generate the maximum air flow. If the engine were operated in the A/B mode, the flow rate would increase.

Therefore, the nominal margin of safety used in this design will be 50 percent. The actual margin of safety is 46.97 percent. This margin of safety is also necessary due to the uncertainty of the most appropriate face velocity in the baghouse.

The proposed design for this study is a baghouse using tubular fiberglass bags. Their durability to withstand operating exposure temperatures up to 550$^{\circ}$F for long durations makes them desirable. The melting temperature of fiberglass is 1470$^{\circ}$F, and it is also resistant to mineral and organic acids. The type of fiberglass chosen should be the continuous-filament type with smooth surface and absence of fibers. This will facilitate cleaning of the bags. Since the specific cleaning and caking characteristics of the particulate deposit are not known, a face velocity of two feet per minute has been used in the design calculations. The design flow rate of 800,000 actual cubic feet per minute, the face velocity and bags with an eight inch diameter and 22-foot length (Reference 12), dictate the use of approximately 4500 bags; see Appendix I.

To accomodate 4500 bags, a design utilizing a subunit approach is suggested. The baghouse will be made up of 90 subunits, each subunit consisting of 50 bags (5 bags by 10 bags). The bags will be spaced four inches apart (i.e., 12-inch centers. See Figure 8). The overall baghouse, in plan view (Figure 9), will be divided into three sections. This particular arrangement will allow for any one of the three sections to be closed for maintenance while the other two have full capacity to handle the expected air flow during military power testing. Two of the three sections will house 36 subunits (four subunits wide by nine subunits long) and the middle section will house 18 subunits (two subunits wide by nine subunits long). These three sections will be divided by walls to facilitate maintenance. A 2-foot walkway surrounding each subunit will be incorporated in the design to allow for easy access during bag replacement. Each subunit will also have an individual shaker frame to provide for cleaning of the 50 bags.

The baghouse should be of the bottom-feed type to allow the dust-laden gas to be brought through the baghouse hoppers and then to the interior of the bags. The hoppers will be approximately 7.5 feet high; the ceiling of the hoppers will function as a base to secure the bottom of the bags and also as a floor for maintenance inspections on the bags above.




**DESCRIPTION**

- ONE SUBUNIT FROM THE TEST CELL BAGHOUSE
- TOTAL NUMBER OF SUBUNITS REQUIRED = 90
- 50 BAGS IN EACH SUBUNIT
- TWO FOOT WALKWAY SURROUNDS EACH SUBUNIT FOR BAG ACCESS
- SCALE : 1/2'' = 1'

Figure 8. Baghouse Subunit Plan View

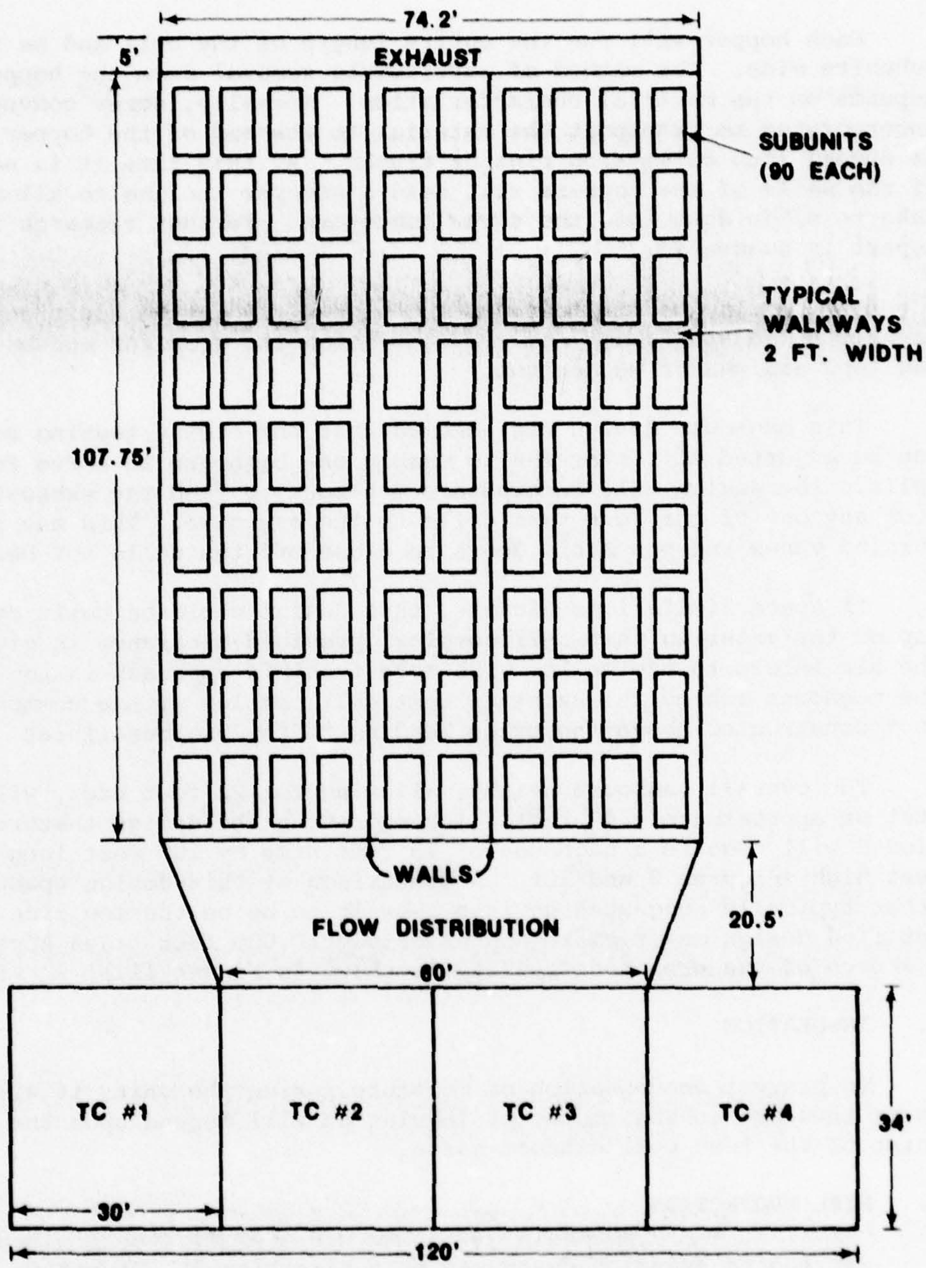



Figure 9. Baghouse in Plan View Connected to Four Test Cells (The roof is not shown to expose the subunit arrangement)

Each hopper will run the entire length of the cell and be two subunits wide. The method of particulate removal from the hoppers depends on the material characteristics. Normally, screw conveyors are incorporated to transport the material to the end of the hopper where it is dumped into collection bins or trucks. At this time it is not known if the walls of the hoppers will need a steeper incline to allow the cake to slide down into the screw conveyors. Further research into this aspect is suggested.

A floor located midlevel to the bags will provide additional access as well as an upper bag deck 7.5 feet below the roof for access to the bag tops and shaker mechanisms.

This baghouse design has assumed that the engine testing schedule can be adjusted at Tinker AFB to enable one baghouse to serve four test cells. The design will incorporate ductwork to feed the exhaust gases from any one of the four test cells to the baghouse. This may involve turning vanes and pneumatic doors to close off the cells not being used.

If space limitations dictate, this design could be built over the top of the existing test cell complex, provided clearance is given for the air inlets to the cells. The more feasible approach is to locate the baghouse behind the existing test cell complex with a common exhaust duct constructed above the cells leading to the baghouse inlet.

The overall baghouse height, allowing for 22-foot bags, will be 37 feet or approximately 40 feet. Incorporating the design features mentioned will require a baghouse of 75 feet wide by 108 feet long by 40 feet high (Figures 9 and 10). A comparison of this design space with other typically suggested designs show it to be on the low side. A more detailed design may require approximately 10,000 feet$^2$ (See Appendix I. A sketch of the proposed facility is shown in Figure 11.).

3. INSULATION

To prevent condensation of moisture inside the unit, it will have to be insulated. The amount of insulation will depend upon the dew point of the test cell exhaust gases.

4. FIRE PROTECTION

Jet engine emission dusts may be a fire hazard. Therefore (Reference 12):

(1) Use flame-proof bags; treatments can be applied to the bags which will not support combustion.

(2) Install filter bag ground wires, which are braided copper wires sewn in the seams of the filter bag and fastened to the tube sheet to drain static electricity from the bag. This guards against sparks as well.

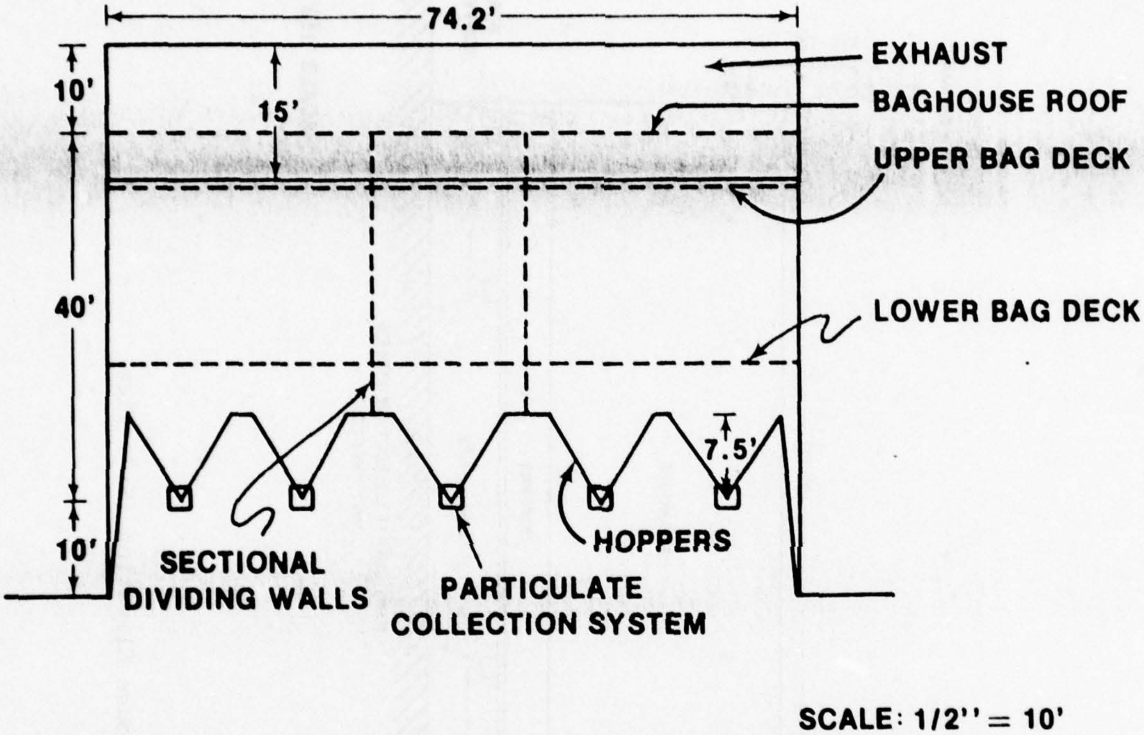



Figure 10. Baghouse End View

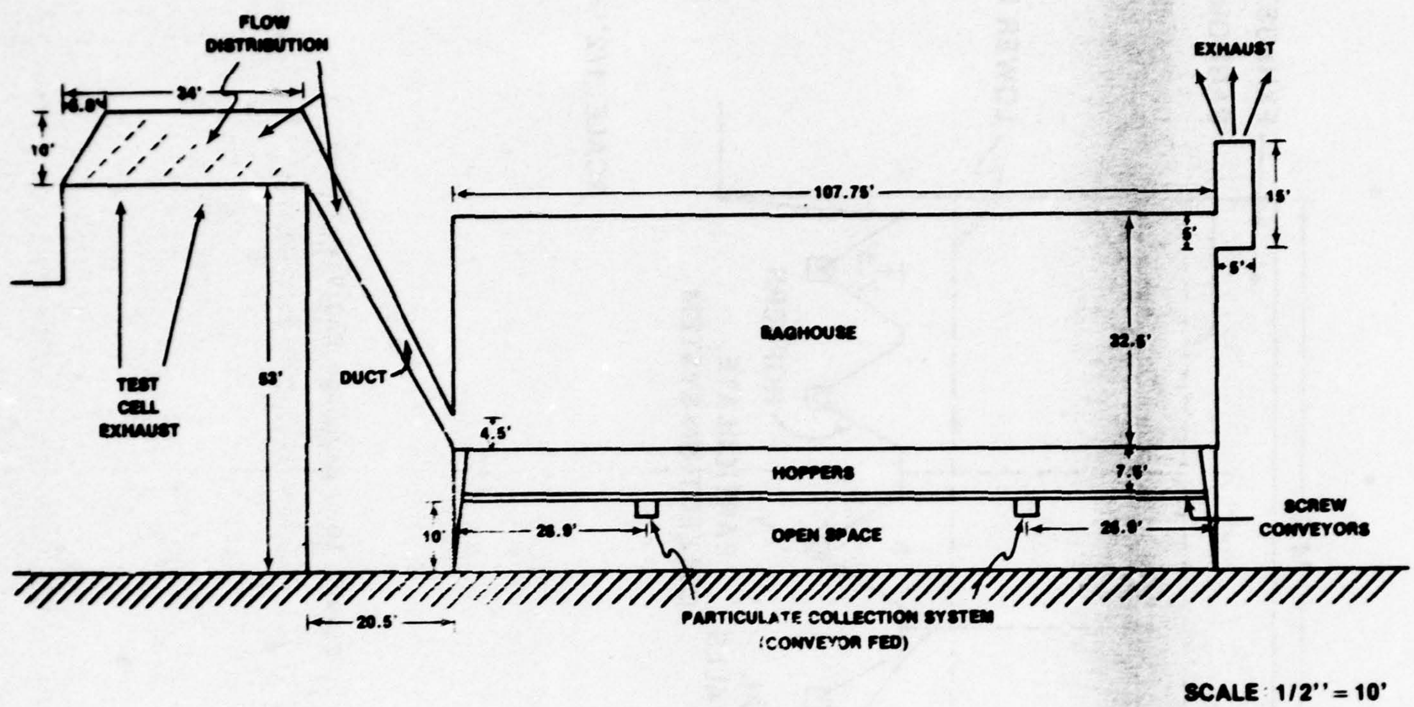



Figure 11. Baghouse Elevation (Side View)

(3) Install explosion vents and explosion doors.

(4) Install sprinkler systems. $CO_2$ fire prevention systems are sometimes installed to prevent damage to bags if the system malfunctions.

5. DEW POINT

A rule of thumb used is that the dew point temperature of the gas stream be approximately $100^{\circ}F$ less than the average temperature of the gas stream entering the unit. Preheating the unit may be necessary possibly by using the jet engine in a low mode of operation. Engines are nearly universally run at idle prior to high power runs so this should not represent a problem.

6. PRESSURE DROP

At present, there is no theoretical method to predict what the pressure drop will be during operation of a fabric filter on a given dust. In general, as particles accumulate, resistance to gas flow and pressure drop across the filter increase. The accumulated deposits are removed periodically by cleaning the fabric to maintain practical head loss.

Total pressure drop throughout the entire baghouse is important in this application due to restrictions of the jet engine. The objective of a test cell is to provide an environment which will allow repeatable tests to be performed on an engine in conditions similar to those experienced in flight. Therefore, excessive resistance to the engine exhaust cannot be tolerated.

Total resistance across a fabric filter is a combination of resistance due to added cake (buildup of particles forming a layer on the material) and residual drag, which is a major portion of the total resistance (estimated to be 0.5 to 1.5 inches of $H_2O$/ft/min (Reference 13). Residual drag is the resistance after the dust-fabric combination has been cleaned and is dependent upon (Reference 13): (1) mode of cleaning, (2) type of filter, and (3) type of dust and filtration velocities.

a. Mode of Cleaning

Residual drag is influenced by the amount of material shaken from the fibers during cleaning. The bags would be cleaned via mechanical shaking mechanisms since the emission rate does not justify continuous cleaning methods. The bag suspension system would be of the frame or rack type. When cleaning glass fiber, the shaking action is almost a total horizontal movement with a lower frequency than that normally used (Reference 12). The vertical component is reduced or eliminated by use of springs or by modifications to the off-the-shelf mechanisms. For glass fiber one source suggests shaking with a period of about 50 cycles/min and amplitude about 5 percent of the bag length (Reference 14). Bag life with fiberglass bags operating at $500^{\circ}F$ and being cleaned mechanically is in the range of three years (Reference 12).

The bag life is dependent on the frequency of flexing. If frequent cleaning is not required, the bag life may be extended. A study of Appendices E, G, and H reveals that the amount of particulate matter collected per run is small compared to most baghouse applications. Table 13 summarizes the particulate accumulation rate with time and number of tests performed in one test cell complex. The accumulation rate of particulate on the bags is low enough that it may take a month or two of testing before the baghouse will require cleaning. This indicates that the cleaning frequency will be very low, perhaps on the order of weeks or months. A prototype model would allow further study of this aspect and may reveal that bag life will be extended, cutting down on projected costs and maintenance. (This is possible especially since the temperature of this exhaust will be at $350^{\circ}F$ and not $500^{\circ}F$.)

The maximum terminal bag resistance (the resistance of the dust-fabric combination prior to cleaning) in this application is 10 inches $H_2O$. (If use of the bag filter absorbs noise sufficiently, then the present noise suppressors could be removed from the test cell exhaust stack and the maximum terminal bag resistance could then be 20 inches $H_2O$.) With a relationship between maximum terminal bag resistance and residual bag resistance, the time between cleaning may be determined to keep the total resistance at an acceptable level (see Figure 12). When the terminal drag is reached, a cleaning cycle should be initiated.

b. Type of Filter

Clean filter air resistance to flow is dependent on fiber structure and the weave of the cloth. A tight weave offers more resistance to flow than a looser weave at the same flow rate.

c. Type of Dust and Filtration Velocities

The relationships between the pressure drop across the cloth and dust cake, the velocity through the cloth and cake and the gas viscosity involve fundamental filtration mechanisms. These are a basic part of the economics of operating a fabric filter system. For practical purposes, the pressure-velocity relationship can be expressed as Darcy's Law. Although more sophisticated relationships can be extracted via fluid mechanics theory through solutions of the Navier-Stokes equation, there is little application for such refinement.

The principle that pressure drop across a porous bed is proportional to the flow through it, is basic to intragranular flows. Darcy's equation can be written as:

$$\frac{\Delta P}{L} = \frac{u_f V}{K}$$

TABLE 13. BAGHOUSE PARTICULATE ACCUMULATION RATE FOR ONE TEST CELL COMPLEX

| Number of Tests | Time | Particles Collected (lb) |
|---|---|---|
| 1 | 4 hours | 5.9 |
| 87 | 1 month | 509.8 |
| 346 | 4 months | 2039.1 |
| 519 | 6 months | 3058.6 |
| 692 | 8 months | 4078.2 |
| 1038 | 12 months | 6117.3 |

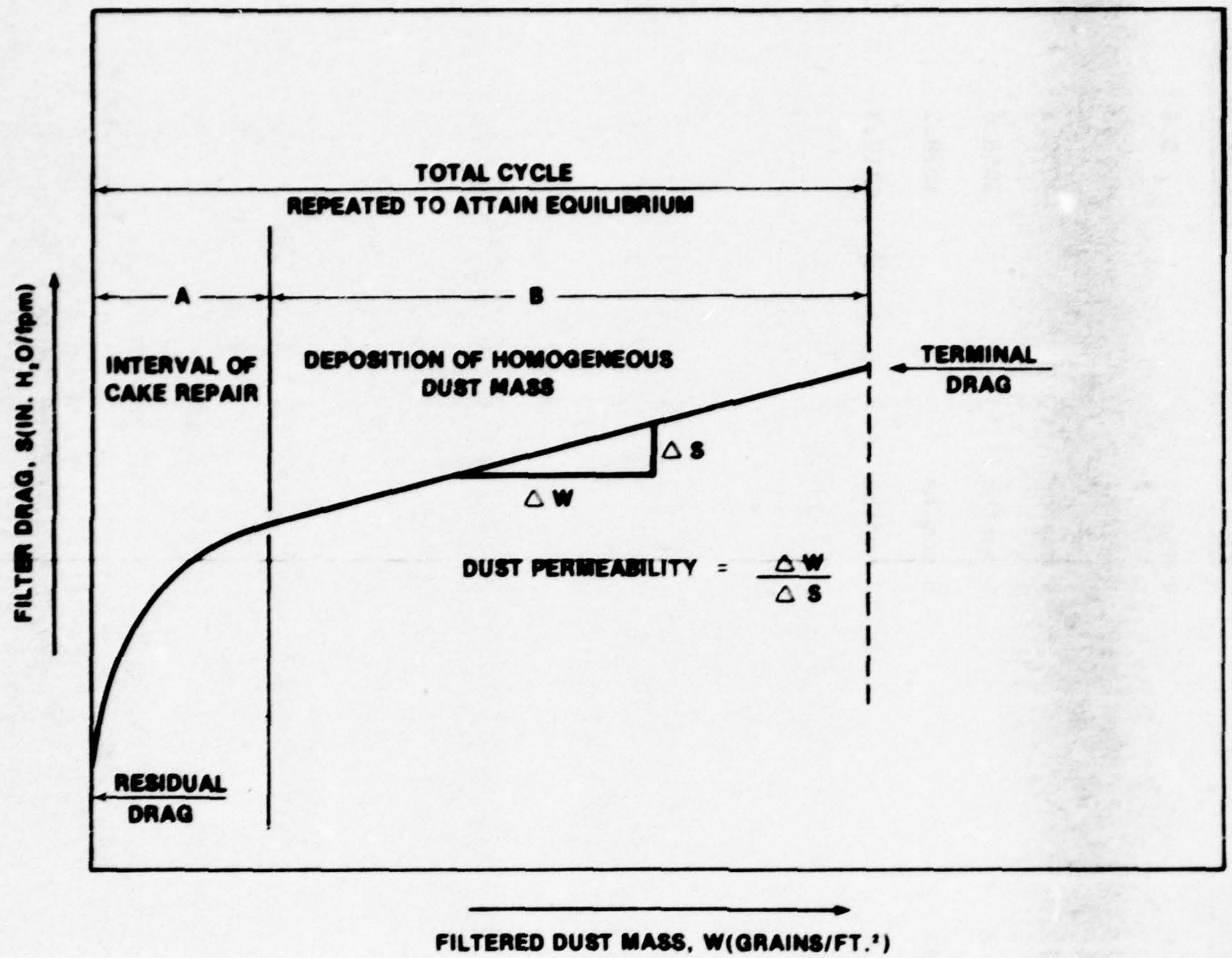



Figure 12. Schematic Representation of Basic Filter Performance Parameters (Reference 14)

which states that the pressure difference across the bed depends on the bed depth, L, gas viscosity, $u_f$, the permeability of the bed, K, as well as on velocity, V (where V = volumetric flow approaching the filter bed divided by the cloth area). All variables are readily obtained engineering parameters except for permeability (K). Note that pressure drop is proportional to the superficial face velocity, which is an important design parameter.

Darcy's Law relating pressure drop and velocity has the following restrictions:

(1) The flow should be only slightly compressible or not at all.

(2) The pressure drop across the bed should be but a small percentage of the ambient pressure.

(3) The flow should be steady (no sharp pulses that could excessively compress the gas).

(4) The flow rate should be low enough so that the resistance to flow is determined by viscous and not inertial effects (at high flow rates Darcy's equation can be modified).

Permeability is the openness of a material to the transmission of fluid and is defined by the above equation. It is experimentally determined by measuring pressure drop across a fixed bed length at a given velocity (Reference 15).

There are large differences in the porosity of dust accumulations and differences in cake structure. Analysts have traditionally concentrated on size, porosity and structure in trying to predict permeability. Many permeability theories have been proposed but none have been widely accepted because of difficulties in predicting porosity and bed structure.

In general, a high value of permeability implies a dust easy to filter. A low value of permeability means that high pressure drop may be expected along with filter velocity problems (Reference 13). Permeability of a dust and filter combination is influenced by (Reference 15): (1) particle size, (2) size distribution, (3) particle shape, (4) surface characteristics, and (5) manner of cake formation.

The pressure drop through a baghouse is difficult to predict without studying similar applications in industry. Nearly all the carbon black plants in the United States which utilize baghouses incorporate fiberglass bags.

To solve the unknowns of permeability and pressure drop, consideration must be given to testing various samples of bag material in a prototype baghouse on a predetermined scale. More preliminary data could be obtained by exposing simple squares of material to the test cell exhaust.

7. SHOCK WAVES

Additional study should be performed to find the effects of engine ignition on the baghouse structure. During engine startup a pressure wave will propogate through the ductwork into the baghouse. This rapid change in pressure will immediately flex the bags as the pressure equalizes throughout the system. This shock wave must not be strong enough to rupture the bags or the structure itself. It may be possible to utilize this pressure front as a cleaning mechanism.

8. SIMILAR APPLICATIONS

Finally, the most encouraging of all are industries with similar emissions at high temperatures who have been using baghouses for some time. These include (in summary) (Reference 16):

(1) Gray Iron Cupola - whose particulate matter is very fine metal oxide fume at 450°F; glass fiber bags, 11½ inch diameter x 15½ feet high; mechanical shakers; face velocity 2.5 fpm; bag life 1 - 2 years operated 20 - 40 hrs/wk.

(2) Carbon Black - particulate is carbon from thermal cracking of HC's such as natural gas or petroleum, use bag collapse with supplementary shaking; bags 5 inches diameter x 11½ feet high; face velocity 1.5 fpm; bag life 12 - 18 months (they must stay above 250°F, otherwise, they are below the acid dew point and it causes corrosion).

9. PROPOSALS

(1) A pilot baghouse should be constructed to study cleanability and required frequency of cleaning.

(2) Loading on sample fabrics should be studied to determine caking characteristics, "blinding" problems and pressure drop.

(3) Development should be started on techniques of rapidly locating bag failures.

(4) Measurements of potential explosive compounds should be taken and compared with lower explosive limits. This should include concentrations due to particulate buildup on the bags, during and between testing.

(5) Studies should be performed on the potential shock waves that could travel through the baghouse due to the engine fluctuations and startups. This study should include the potential use of these fluctuations as a cleaning mechanism.

(6) The slope required for the hopper walls should be determined by study of the particulate adhesion characteristics.

## SECTION VIII

## COSTS

### 1. INTRODUCTION

A cost study has been completed to determine the annual operating cost for a baghouse and a packed bed scrubber. These costs are then compared in tabular form. The initial costs for both units will be spread over a 15-year period. Construction will be assumed for 1980 and all costs are adjusted to that year. Figures calculated from past costs are adjusted for a six percent annual inflation rate. Each analysis consists of four parts: installed costs, utilities, maintenance and operating costs and maintenance materials costs. These costs are compared on a yearly basis.

This comparison is made on the basis of one control device for one test cell. However, with the present test cell complex arrangement at Tinker, a more feasible approach would allow for all four cells to exhaust into one baghouse. This arrangement will also be addressed in the analysis.

### 2. BAGHOUSE COSTS

Installed Costs (Reference 13, 1973 Figures): $\$1.25/ft^3$ for the unit and up to three times that amount installed.
1.25 (3) 800,000 cfm = \$3,000,000

Adjust for inflation of 6 %/yr. Assume construction is in 1980.

Adj. Installed Cost $= (1.06)^7\ (3 \times 10^6) = \$4.5 \times 10^6$

Amortization of Costs

Assume 9.0% interest

Lifetime 15 years

$$R = P \frac{i\,(1 + i)^n}{(1 + i)^n - 1}$$

where: R = uniform payments, annual (dollars)

P = present sum of money

i = interest rate

n = number of interest periods (years)

$$R = 4{,}500{,}000 \; \frac{0.09\,(1 + 0.09)^{15}}{(1 + 0.09)^{15} - 1}$$

$$= \$558{,}264 \text{ per year}$$

Maintenance (Reference 18): This includes maintenance, bag replacement and power.

$$G = \frac{S(0.7457PHK + M)}{6356E}$$

where: P = pressure drop

H = hours of operation annually

K = cost of electricity in dollars per kilowatt-hour

M = maintenance cost per acfm in dollars per cfm

E = fan efficiency expressed as a decimal (use as one in this case since no fan is necessary)

S = design capacity of the unit in acfm

G = annual costs in dollars for operating and maintenance

$$G = \frac{800{,}000\ (0.745(4)\ 2768\ (0.017) + 0.08)}{6356}$$

$$= \$17{,}660 \text{ per year}$$

Corrected for year of construction

$(1.06)^9$ \$17,660 = \$29,836 per year

Utilities (Maintenance ventilation and lighting)

This cost is an estimate based on the 1973 cost (Reference 17).

(2) \$500 $(1.06)^7$ = \$1500 per year

Maintenance Materials (Reference 2):

$(1.06)^7$ 21,000 = \$31,576 per year

3. PACKED BED SCRUBBER COSTS

Installed Costs: A recent comparison of detailed costs for this system shows some discrepancy (Reference 1). This study assumes that the Naval Air Rework Facility at Jacksonville, Florida, has the most accurate data.

Installed cost = \$1,945,000

Amortization of Costs

Assume 9.0% interest

R = \$241,294

Maintenance

$\$18,000\ (1.06)^7 = \$27,065/yr$

Maintenance Materials

$\$12,000\ (1.06)^7 = \$18,044/yr$

Utilities and Chemicals: This analysis was based on a four-hour test using 9291 kwh/test and 266 gpm of $H_2O$. The cost of chemicals required came from a ratio technique with the 1973 calculated costs. This assumes a testing frequency of approximately 22 engines/month/cell, \$215,841/yr.

4. FOUR-CELL BAGHOUSE COSTS

With some minor adaptations the baghouse can be made to accomodate an entire test cell complex at Tinker AFB. Appendices E and H and Table 13 verify that the baghouse could handle exhaust from four test cells with modifications in testing schedules. The main difference in the baghouse would be the inlet duct work. This would be modified to include all four-cell exhaust stacks. Therefore, additional costs would be incurred for materials and labor, including ductwork and a flow distribution system which will direct the exhaust from any cell and evenly distribute it to the baghouse. This could involve louvers as well as pneumatic doors to seal off cell exhaust stacks not being used. A rough estimate for this type of system installed is an additional $\$1.5(10^6)$ with some increases in utilities and maintenance. Complete cost comparisons are shown in the following section.

## 5. COST COMPARISON

There is a large difference between the 1973 cost comparisons and this analysis. The primary differences are in the system installed costs and the utilities. The 1973 cost analysis assumed that metal construction could be used in the scrubber. However, the prototype scrubber in Jacksonville has shown this to be unacceptable for extended usage. Instead, concrete has been successfully used with an increase in expected scrubber lifetime as well as a cost increase. The utilities have also seen a tremendous cost increase over the last seven years. The water and electric costs are dependent on the cell usage. It is possible that the 1973 costs were projected on a lower usage rate than is used in this analysis. The 1973 analysis indicated that on an annual basis the scrubber costs would be 27 percent of the baghouse costs. This analysis indicates that now the scrubber cost will be 80 percent of the baghouse costs. As the cost of utilities increases, the annual scrubber cost will approach that of the baghouse. Table 14 summarizes the analysis of these two control techniques as well as the baghouse adapted to control one test complex (i.e., four individual cells).

The cost table includes three parameters for cost comparison: the total annual cost, cost per $ft^3$/minute of air cleaning capability and cost per pound of particulate collected.

TABLE 14. COST COMPARISON OF A BAGHOUSE AND PACKED BED SCRUBBER

| Parameter | One Cell Packed Bed Scrubber | One Cell Baghouse | Four Cell Baghouse (per Cell) |
|---|---|---|---|
| Installed Cost | 1,945,000 | 4,500,000 | 6,000,000 |
| Amortization of Installed Cost | 241,294 | 558,264 | 744,352 |
| Maintenance | 27,065 | 29,836 | 59,672 |
| Maintenance of Materials | 18,044 | 31,576 | 63,152 |
| Utilities and Chemicals | 215,841 | 1,500 | 6,000 |
| Total Annual Cost (over 15 years) | 502,244 | 621,176 | 218,294 |
| Cost per $ft^3$/min of air cleaning capability | 0.80[1] | 0.78[2] | 0.27[2] |
| Cost per lb of particulate collected | 500[3] | 431[4] | 152[4] |

1. The baghouse flow rate of 800,000 acfm was corrected to a corresponding flow rate at a lower temperature and higher humidity for the scrubber.

2. Based on the baghouse design rate of 800,000 acfm.

3. Based on an average collection efficiency of 66%. See Table 6, where the efficiency range is 47% to 85%. During some tests greater than 50% of the particulate was collected in the sump water and not in the scrubber.

4. Based on a collection efficiency of 95%.

# SECTION IX

## CONCLUSIONS

1. It is feasible to control turbine engine test cell particulate emissions with a baghouse, under the conditions assumed in this report.

2. The air flow volumes, at the conditions stated, are not excessive for control with a baghouse.

3. Both excess and augmentation air sufficiently dilute the exhaust gas to temperatures permissible in baghouse operation.

4. With the baghouse properly insulated, the temperature of the exhaust gas stream will remain above the dew point, thereby preventing condensation.

5. The application of a baghouse to control particulate emissions is becoming more economical. In some respects ($/acfm and $/lb of particulate collected) a baghouse is currently less expensive than a packed bed scrubber.

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APPENDIX A

COMBUSTION EQUATIONS

$C_8H_{18}$ Octane

$$C_8H_{18} + 12\frac{1}{2}\ (O_2 + 3.76\ N_2) \rightarrow 8CO_2 + 9H_2O + 47\ N_2$$

$C_9H_{20}$ Nonane

$$C_9H_2O + 14\ (O_2 + 3.76\ N_2) \rightarrow 9CO_2 + 10H_2O + 52.6\ N_2$$

Air Required for Complete Combustion

$C_8H_{18}$ requires 15.11 lb air/lb $C_8H_{18}$

$C_9H_{20}$ requires 15.07 lb air/lb $C_9H_{20}$

JP-4 is nominally 43% $C_9H_{20}$, 57% $C_8H_{18}$

therefore:

$$\frac{0.57\text{ lb }C_8H_{18}}{\text{lb fuel}}\left(\frac{9220\text{ lb fuel}}{\text{hr}}\right)\frac{15.11\text{ lb air}}{\text{lb }C_8H_{18}} = 79{,}409\text{ lb air/hr}$$

$$\frac{0.43\text{ lb }C_9H_{20}}{\text{lb fuel}}\left(\frac{9220\text{ lb fuel}}{\text{hr}}\right)\frac{15.07\text{ lb air}}{\text{lb }C_9H_{20}} = 59{,}747\text{ lb air/hr}$$

Total = 139,156 lb air/hr

Excess Air

$$\frac{139{,}156\text{ lb/hr} - 856800\text{ lb/hr}}{139{,}156} = 5.16\text{ or }516\%\text{ excess air}$$

For this calculation, assume the $H_2O$ in the 139,156 lb air/hr used in combustion stays with the excess air.

Specific Humidity (SH)

Psychrometric chart for air @ 59°F and 70% relative humidity

$$SH = 0.008 = \frac{x\text{ lb }H_2O}{y\text{ lb dry air}}$$

Moisture

or 0.008 (y lb d.a.) = x lb $H_2O$ (1)

recall: 856,800 total lb air = x lb $H_2O$ + y lb d.a. (2)

substitute (1) into (2)

856,800 = 0.008 (y lb d.a.) + y lb d.a.

856,800 = 1.008 (y lb d.a.)

850,000 = y lb d.a. 850,000 lb d.a./hr

from (1)

.008 (850,000) = x lb $H_2O$ = 6800 lb $H_2O$/hr

Excess Air and Moisture Chemistry

Moisture - on a mole basis (the ultimate combustion equation will be on a per-lb-of-fuel basis)

120 lb fuel/mole fuel = 0.57 (MW $C_8H_{18}$) + 0.43 (MW $C_9H_{20}$)

$$6800 \frac{\text{lb } H_2O}{\text{hr}} \left(\frac{\text{hr}}{9220 \text{ lb fuel}}\right) \left(\frac{120 \text{ lb fuel}}{\text{mole of fuel}}\right) = 88.5 \text{ lb } H_2O/\text{mole of fuel}$$

$$\frac{88.5 \text{ lb } H_2O}{\text{mole of fuel}} \left(\frac{\text{mole } H_2O}{18 \text{ lb } H_2O}\right) = 4.9 \frac{\text{moles of } H_2O}{\text{moles of fuel}}$$

Air

856,800 total - 6800 lb $H_2O$ - 139,156 lb d.a. = 710,844 lb da/hr

$$710844 \frac{\text{lb da}}{\text{hr}} \left(\frac{\text{hr}}{9220 \text{ lb fuel}}\right) \frac{120 \text{ lb fuel}}{\text{mole}} = 9252 \text{ lb da/mole of fuel}$$

$$\frac{9252 \text{ lb da}}{\text{mole fuel}} = x(O_2 + 3.76\ N_2)$$

$$= x(32 + 3.76\ (28))$$

$$9252 = x(137.3)$$

$$x = 67.4$$

Therefore, to the fuel add 67.4($O_2$ + 3.76 $N_2$) + 4.9 $H_2O$

To find the total volume of exhaust products, find the density of this gas from:

$$\partial = \frac{P}{RT}$$

So find the gas constant, R, from a mixture calculation, obtain the lb moles of products from the balanced reaction equation.

Reaction Equations

(I) $0.57 \,[C_8H_{18} + 12\tfrac{1}{2}\,(O_2 + 3.76\,N_2)] + 0.43\,[C_9H_{20} + 14\,(O_2 + 3.76\,N_2)]$

$+ 67.4\,(O_2 + 3.76\,N_2) + 4.9\,H_2O \rightarrow 0.57\,[8CO_2 + 9H_2O + 47.2\,N_2]$

$+ 0.43\,[9CO_2 + 10H_2O + 52.8\,N_2] + \underbrace{67.4\,(O_2 + 3.76\,N_2)}_{\text{air}} + \underbrace{4.9\,H_2O}_{H_2O}$

(II) 0.57 moles $C_8H_{18}$ + 0.57 (12.5) moles $O_2$ + 0.57 (3.76) 12.5 moles $N_2$ + 0.43 moles $C_9H_{20}$ + 0.43 (14) moles $O_2$ + 0.43 (14) 3.76 moles $N_2$ + (air) + ($H_2O$) $\rightarrow$ 4.56 moles $CO_2$ + 5.13 moles $H_2O$ + 26.9 moles $N_2$ + 3.87 moles $CO_2$ + 4.3 moles $H_2O$ + 22.7 moles $N_2$ + 67.4 moles $O_2$ + 253.4 moles $N_2$ + 4.9 moles $H_2O$

(III) in lbs (look at products only)

$\rightarrow$ 200.6 lb $CO_2$ + 92.35 lb $H_2O$ + 753.3 lb $N_2$ + 170.3 lb $CO_2$ + 77.4 lb $H_2O$ + 635.7 lb $N_2$ + 2156.8 lb $O_2$ + 7095.9 lb $N_2$ + 88.2 lb $H_2O$

(IV) when 120 lb fuel are burned (i.e., on a per lb fuel basis)

$\rightarrow$ 1.67 lb $CO_2$ + 0.77 lb $H_2O$ + 6.28 lb $N_2$ + 1.42 lb $CO_2$ + 0.64 lb $H_2O$ + 5.3 lb $N_2$ + 17.97 lb $O_2$ + 59.1 $N_2$ + 0.73 lb $H_2O$

(V) Total Products/lb of Fuel

$3.09$ lb $CO_2$ + $1.41$ lb $H_2O$ + $0.73$ lb $H_2O$ + $11.58$ lb $N_2$ +

$77.1$ lb air

where:

$1.41$ lb $H_2O$ is from the fuel and theoretical air

$0.73$ lb $H_2O$ is from the moisture in the excess air

(VI) $28{,}490 \ \frac{\text{lb } CO_2}{\text{hr}} + 13000 \ \frac{\text{lb } H_2O}{\text{hr}} + 6731 \ \frac{\text{lb } H_2O}{\text{hr}}$

$+ 106768 \ \frac{\text{lb } N_2}{\text{hr}} + 710862 \ \frac{\text{lb d.a.}}{\text{hr}} \rightarrow 846120$ lb dry gas/hr

and 19731 lb $h_2O$/hr

Check if this total is the same as that from the mass balance:

| | |
|---|---|
| Mass Balance | 856800 lb air and $H_2O$ in |
| | + 9220 lb fuel in |
| | 866020 lb products |
| Reaction Equations | 846120 lb dry air and dry combustion product out |
| | + 19731 lb $H_2O$ out |
| | 865851 lb products |

Difference = 866020 - 865851 = 169 lb

This 169 lbs represents inherent calculation inaccuracies; since it is such a small percentage of the total flow the difference will be ignored.

## APPENDIX B

## MIXTURE CALCULATION

| Component | lb moles[a] | $X_i$ (lb M/lb M mix) | $\hat{M}_i$ (lb m/lb M) | $\hat{M}_i/n$ (lb m/lb M mix) |
|---|---|---|---|---|
| $CO_2$ | 8.43 | 0.021 | 44 | 0.924 |
| $H_2O$ | 14.33 | 0.036 | 18 | 0.648 |
| $H_2$ | 303.0 | 0.771 | 28 | 21.59 |
| $O_2$ | 67.4 | 0.171 | 32 | 5.47 |
| Total | 393.16 | 1.000 | $\hat{M}$ = 28.63 lb m/lb M | |

* M = mole
m = mass

*(a) See reaction equation (II) add mole products*

**Constant for Product Mixture**

$$R = \frac{R}{\hat{M}} = \frac{1545}{28.63} = 53.96 \text{ ft- lbf/lb m-}^{\circ}\text{R}$$

**Density** of engine exhaust

$$\rho = \frac{P}{RT} = \frac{28.4 \text{ lbf/in}^2 \ (144 \text{ in}^2/\text{ft}^2)}{53.96 \text{ ft-lbf/lbm-}^{\circ}\text{R}(579 + 460^{\circ}\text{R})}$$

$$\rho = 0.73 \text{ lbm/ft}^3$$

## APPENDIX C

## GAS FLOW THROUGH CONTROL DEVICE

<u>Air Flow</u> - Maximum flow in military mode to be handled is 1.8 times the amount required for the engines as given in the fuel/air ratio (mass)

1.8 (856800 lb/hr) = 1,542,240 lb/hr to the control device

<u>Mass Balance</u>

| | |
|---|---|
| 856800 lb/hr air | 676220 lb/hr |
| @ 59$^\circ$F 70% RH | @ 59$^\circ$F 70% RH |
| 9220 lb fuel/hr | Combustion products @ 579.1$^\circ$F<br>28.4 psia, 866020 lb/hr |

<u>Augmentation Air Flow</u>

1,542,240 lb/hr - (856800 lb air/hr + 9220 lb fuel/hr) =

676220 lb augmentation air/hr

<u>Volume of Combustion Products</u>

866020 lb/hr (ft$^3$/.073 lbm)* = 11,863,287 act. ft$^3$/hr

$$= 11{,}863{,}287 \ \frac{\text{actual ft}^3 \text{ combust. prod.}}{\text{hr}}$$

*Density factor comes from Appendix IV

<u>Moisture of Augmentation Air</u>

Ambient conditions

SH = 0.008 lb $H_2O$/lb d.a.

676220 lb air/hr = lb d.a. + lb $H_2O$ = lb d.a. + .008 lb d.a.

$$\frac{676220}{1.008} = \text{lb d.a.} = 670853 \text{ lb d.a./hr}$$

676220 - 670853 = 5367 lb $H_2O$/hr

Total Vol in Aug. Air

= vol. d.a. + vol. $H_2O$

from psych. chart @ ambient conditions

13.23 $ft^3$/lb d.a.

from "Marks" $H_2O$ @ $59^oF$ = 62.37 lb/$ft^3$

Therefore,

$$670853 \text{ lb d.a./hr } \left(\frac{13.23 \text{ ft}^3}{\text{lb d.a.}}\right) + 5367 \text{ lb H}_2\text{O/hr } \left(\frac{\text{ft}^3}{62.37 \text{ lb}}\right) =$$

$$8{,}875{,}385 \text{ ft}^3/\text{hr} + 86.0 \text{ ft}^3/\text{hr} =$$

$$8{,}875{,}471 \ \frac{\text{actual ft}^3 \text{ of aug. air}}{\text{hr}}$$

Find the Temperature of Combined Gases (i.e., the combustion products and the augmentation air).

$$\frac{11.86\ (10^6)\text{ft}^3/\text{hr } 579.1^o + 8.88\ (10^6)\text{ft}^3/\text{hr } 59^o}{20.74\ (10^6)} = 356.5^oF$$

Find Specific Humidity of Gas Mixture

$$\frac{\text{Total lb H}_2\text{O in exhaust + aug. air}}{\text{Total lb d.a. in exhaust + aug. air}}$$

$$= \frac{19731 \text{ lb H}_2\text{O} + 5367 \text{ lb H}_2\text{O}}{846120 \text{ lb d. gas} + 670853 \text{ lb d.a.}} = \frac{25098 \text{ lb H}_2\text{O}}{1516973 \text{ lb d. gas}}$$

= 0.0165 lb $H_2O$/lb dry gas

Assume exhaust gas is similar to air. Therefore, use the psych. chart.

Find 0.0165 lb $H_2O$/lb dry air = 116 gr $H_2O$/lb d.a. and $356.5^oF$ to establish the dew pt.

From the psych. chart obtain the following data:

Dew Point = $80^oF$      h = 100 Btu/lb d.a.

Wet Bulb = $115^oF$      v = 21 $ft^3$/lb d.a.

Total Volume to Control Device

$$1516973 \ \frac{\text{lb d.a.}}{\text{hr}} \ \frac{21 \ \text{ft}^3}{\text{lb d.a.}} + 25098 \ \frac{\text{lb } H_2O}{\text{hr}} \ (32.0 \ \text{ft}^3 \ \text{lb})^* = 32,659,569$$

$= 32.66 \ (10^6) \ \text{ft}^3/\text{hr}$

$= 544,326$ actual $\text{ft}^3/\text{min}$

* $\partial H_2O$ @ 356.5°F = 180.3°C from superheated steam tables @ 14.7 psia

$= 32.0 \ \text{ft}^3/\text{lb m}$

## APPENDIX D

## HEAT LOSS IN THE TEST CELL

The purpose of this calculation is to find out if the temperature drop from the exhaust of the engine to the stack exhaust is significant. If it is, the volume of air flow will be reduced from that calculated.

Assume that conduction is the most prevalent form of heat loss.

$$\dot{q} = - \frac{kA}{\Delta x} (T_2 - T_1)$$

where:

$K$ = thermal conductivity

$= 0.5$ Btu/hr-ft-$^{\circ}$F

$A$ = total wall area exposed

= 3.5 exhaust stack wall surface areas

$= 3.5\ (45)\ (29) = 4567.5\ \text{ft}^2$

$T_2 = 356.6^{\circ}$F = temperature of mixed gas stream

$T_1 = 59^{\circ}$F = ambient temperature

$\Delta x$ = 1 ft = wall thickness

$$q = - \frac{0.5\ (4567.5)}{1} (356.5 - 59)$$

$q = -679416$ Btu/hr through the walls

Heat generated from the fuel alone:

$$9220 \frac{\text{lbs fuel}}{\text{hr}} \left(\frac{18400\ \text{Btu}}{\text{lb fuel}}\right) = 170\ (10^6)\ \text{Btu/hr}$$

Therefore, the heat loss is insignificant and does not need to be considered in the calculation of exhaust flow rate.

## APPENDIX E

## TINKER AFB TEST CELL USAGE

**Number of Engines:**

$$\frac{173\ \text{engines}}{\text{month}} \quad \frac{12\ \text{month}}{\text{year}} = \frac{2076\ \text{engines}}{\text{hr}}$$

**Total Hours of Operation Per Year:**

$$\frac{4\ \text{hrs}^{*}}{\text{engine}} \quad (2076) = 8304 \quad \frac{\text{hrs}}{\text{yr}}$$

* Many engines will be rejected at less than full runs; therefore, this is a maximum value.

**Total Hours Above Idle:**

$$\frac{2}{3} \quad (8304) = \frac{5536\ \text{hrs}}{\text{yr}}^{**}$$

** This is for the two complexes.

**One Complex (having four individual cells):**

$$\frac{5536}{2} = 2768\ \text{hrs/yr/complex}$$

## APPENDIX F

## SPRAY RING EFFECT

This temperature should be kept $100^{\circ}F$ above the dew point. For the conditions under study the dew point is $80^{\circ}F$. The total volume of gases can be reduced if the spray rings are utilized. This will reduce the size of baghouse required.

Example:

Lower the outlet temperature to $200^{\circ}F$. Following the constant temperature lines from $356^{\circ}F$ to $200^{\circ}F$ yields

$$\text{Specific Humidity} = 0.05 \ \frac{\text{lb } H_2O}{\text{lb d. gas}}$$

$$0.05 = \frac{x \text{ lb } H_2O \text{ hr}}{1{,}516{,}973 \text{ lb d. gas/hr}}$$

$$x = 75849 \text{ lb } H_2O\text{/hr minus the existing } H_2O$$

$$\begin{array}{r} 75849 \\ \underline{-25098} \\ 50751 \end{array} \text{ lb } H_2O\text{/hr } (ft^3/62.4 \text{ lb } H_2O)\ (7.481 \text{ gal}/ft^3)\text{hr}/60 \text{ min}$$

$$= 101 \text{ gal/min needed}$$

New Flow Rate

$$1{,}516{,}972 \ \frac{\text{lb d.a.}}{\text{hr}} \left(\frac{18 \ ft^3}{\text{lb d.a.}}\right) + 75849 \ \frac{\text{lb } H_2O}{hr^2} \ \frac{26.5 \ ft^3}{\text{lb } H_2O}$$

$$= 29{,}315{,}512 \ \frac{ft^3}{hr}$$

$= 488{,}592$ actual $ft^3$/min

or a reduction of 55,734 ACFM*

* $(32{,}659{,}569 - 29{,}315{,}512 = 3{,}344{,}057$ actual $ft^3$/hr)

new dew point $105^{\circ}F$

## APPENDIX G

## POLLUTANT CONCENTRATION

$$\frac{2.21 \text{ lb Particulate}}{1000 \text{ lb fuel}} \quad 9220 \quad \frac{\text{lb fuel}}{\text{hr}} = 20.4 \quad \frac{\text{lb Particulate}}{\text{hr}}$$

Std. Conditions, $32^{\circ}F$, 14.7 psia

$$530{,}941 \ \frac{\text{dry ft}^3}{\text{min}} \left(\frac{14.7}{14.09}\right) \left(\frac{32 + 460^{\circ}F}{356.5 + 460^{\circ}R}\right) = 333781 \text{ dscf/min}$$

$$20.4 \ \frac{\text{lb part.}}{\text{hr}} \left(\frac{\text{hr}}{60 \text{ min}}\right) \ 7000 \ \frac{\text{grains}}{\text{lb part}} \ \frac{\text{min}}{333781 \text{ dscf}} = 0.0071 \text{ gr/dscf}$$

Inlet to control device = 0.0071 grain/dscf

a 95% efficiency will discharge 0.05 (0.007 grains/dscf) = 0.00035 gr/dscf

## APPENDIX H

## EMISSION CALCULATION

**Total Time per Run**

48 + 69 + 108 + 23 = 248 minutes = 4.13 hrs/run

**Operation Time per Year**

692 hrs per year per test cell

2768 hrs per year per test cell complex

**Emissions**

Without Control

$$2.21 \frac{lbs}{hr} \; 692 \frac{hr}{yr} \; \frac{T}{2000 \text{ lb}} = 0.76 \text{ T/yr/cell or } 3.06 \text{ T/yr/complex}$$

With Control (95% efficiency)

(0.05) 0.76 = 0.04 T/yr/cell or 0.15 T/yr/complex

## APPENDIX I

## BAGHOUSE DESIGN CALCULATIONS

### Number of Bags Required (at actual flow)

Specifications

Bag: 8 in dia. by 22 ft high (Reference 12)

Face Velocity 2 fpm (Reference 16)

$$\text{Area per Bag} = 2\pi \left(\frac{8}{12}\right) 22 = 92 \text{ ft}^2$$

$$\text{Area Required} = \frac{544,326}{2} = 272,163 \text{ ft}^2$$

$$\text{Number of Bags} = \frac{272,163}{92} = 2958$$

### Number of Bags Required (at design flow)

Flow Rate 800,000 acfm (Appendix B)

### Bag Area Needed

$$\frac{800,000 \text{ ft}^3/\text{min}}{2 \text{ ft/min}} = 400,000 \text{ ft}^2$$

### Number of Bags Required → Design

$$\frac{400,000 \text{ ft}^2}{92 \text{ ft}^2/\text{bag}} \simeq 4348 \simeq 4500 \text{ bags}$$

### Assumptions

Assume bags are spaced 4 inches apart (i.e., 12-inch centers). See Figures 8 and 9.

Assume bags are in banks of 5 bags x 10 bags with 2 ft on all sides for maintenance (i.e., walkways).

### Design for 4500 Bags

Assume that the maximum number of bags that can be shaken at one time is fifty. Therefore, the entire baghouse will be constructed of subunits as shown in Figure 8.

There are walkways provided between each subunit and around the periphery of the baghouse. The baghouse is designed in three basic sections as shown in plan view of Figure 9.

## Dimensions

### Total Width

$$13 \text{ (2 ft walkways)} + 10 \text{ subunits } (\frac{56}{12} \text{ ft}) + 4 \text{ walls } (\frac{0.375 \text{ ft}}{\text{wall}}) = 74.2 \text{ ft}$$

### Total Length

$$10 \text{ (2 ft walkways)} + 9 \text{ subunits } (\frac{116}{12} \text{ ft}) + 2 \text{ walls } (\frac{0.375 \text{ ft}}{\text{wall}}) = 107.75 \text{ ft}$$

### Total Height

Hopper and ceiling heights are estimated at 15 ft total. Overall baghouse height is 15 ft plus 22 ft = 37 or about 40 ft; (Figure 10).

This design allows lower flow rates to be passed through part of the baghouse. For example, if a flow or (2/3 (800,000)) = 533,333 acfm (which is approximately military mode flow rate) is tested, it can be passed through one side section and the middle section at a face velocity of 2.5 fpm and still satisfy the surface area requirements.

$$\frac{533{,}333 \text{ acfm}}{2.5 \text{ ft/min}} = 213{,}333 \text{ ft}^2$$

$$\frac{213{,}333 \text{ ft}^2}{92 \text{ ft}^2\text{/bag}} = 2319 \text{ bags}$$

One side and the center section contain 20 (90) + 10 (90) = 1800 + 900 = 2700 bags. Therefore, the actual flow will be 2.1 ft/min. So any one section of the baghouse can be out of service and testing at lower engine modes can proceed.

This design allows the possibility to construct the device over 3 test cells (or more in a row, provided clearance is given for the cell inlet air). Hoppers handle two rows of 5 bags each by 9 sections of 10 bags each; they run lengthwise. See Figures 8, 9 and 11.

Ductwork will have to be constructed to provide flow from each cell to the baghouse. This will involve turning vanes and pneumatic doors to close off the cells not being used.

Total baghouse area is 7995 $\text{ft}^2$. (This is very close to the 6627 $\text{ft}^2$ required by the scrubber.)

To compare this design with other typical designs (Reference 13), the normal range of approximate baghouse size for shaker-type installations are:

Low Approximation

$$\frac{8.7\ ft^2 \text{ of collection area}}{1000\ cfm}\ 800{,}000\ acfm = 6920\ ft^2$$

High Approximation

$$\frac{16.9}{1000}\ (800{,}000) = 13520\ ft^2$$

This design area is 7995 $ft^2$ which is on the low side of the range calculated above. A more detailed design may require approximately 10,000 $ft^2$.

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